

# **The Chimpanzee**

A Series of Volumes on the Chimpanzee

2

## **Physiology, Behavior, Serology, and Diseases of Chimpanzees**

UNIVERSITY PARK PRESS











PHYSIOLOGY, BEHAVIOR, SEROLOGY, AND DISEASES OF CHIMPANZEES

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BEHAVIOR, SEROLOGY,  
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VOL. 2

Editor  
G. H. BOURNE, Atlanta, GA



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Baltimore, Maryland

University Park Press

Manchester, England



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130 figures and 69 tables



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 B. C. COLE, Salt Lake City, UT  
 H. E. DALE, Columbia, MO  
 D. N. FARRER, Holloman AFB, NM  
 W. FARRIS, Detroit, MI  
 J. A. GAGNON, Washington, DC  
 M. GOODMAN, Northville, MI  
 C. E. GRAHAM, Atlanta, GA  
 N. B. GUILLOUD, Atlanta, GA  
 H. D. JOHNSON, Columbia, MO  
 H. KALMUS, London  
 S. S. KALTER, San Antonio, TX

W. A. MASON, Covington, LA  
 G. W. MOORE, Raleigh, NC  
 C. R. NOBACK, New York, NY  
 EMILY POULIK, Detroit, MI  
 A. H. RIESEN, Riverside, CA  
 F. H. ROHLES, Jr., Manhattan, KS  
 M. D. SHANKLIN, Columbia, MO  
 SONYA K. SIMENAUER, New York, NY  
 C. CRAIGH TISHER, Durham, NC  
 RUSSELL H. TUTTLE, Chicago, IL  
 J. R. WARD, Salt Lake City, UT  
 W. E. WARD, Colorado, CO  
 F. A. YOUNG, Pullman, WA

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## CHIMPANZEE VISUAL PERCEPTION

A. H. RIESEN

University of California, Riverside, CA

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### INTRODUCTION

Threshold values and differential sensitivities of chimpanzee vision are closely comparable to those for man. Only careful quantitative study has proved adequate to determine differences. The work of making detailed comparisons is most advanced along dimensions of spectral sensitivity thresholds and differential hue discrimination thresholds. Measurements are least advanced thus far in the more complex aspects of spatial pattern perception. The highly competent study of minimum separable acuity in juvenile chimpanzees and young human children by SPENCE [1934] stands as the first crucial experiment in the evaluation of the chimpanzee's capabilities for spatial vision.

Careful naturalistic observation serves to confirm the widely held view that man and chimpanzee are alike in their color, form, and complex spatial discriminative responses. The ape is highly adept in coordinating manual response with visual information. This is evident in the accuracy of leaps made from bough to bough, in the guiding of sticks toward small targets, and in



grooming behavior. In grooming the chimpanzee directs the finger tips to very small blemishes on the skin surface of an animal or human friend.

Observing a chimpanzee in captivity or in the wild prepares one to accept the controlled experimental evidence that his visual acuity is quite like that of a human being of comparable age. Careful naturalistic observation also persuades the thoughtful observer that the ape is more astute in certain observing skills (or habits of observation) than is the man of modern civilized background. Selective figure-ground discriminations based on observing responses as these are reinforced in the native habitat may be difficult to identify under informal field conditions, but the experienced observer sees many suggestions of unique perceptual skills. Some of these have to do with the physical environment, and others indicate that social behavior is most often guided by the detection of subtle cues from expressive movements or postural activities quickly and often fleetingly displayed by another individual of the 'family' group.

The present chapter will be concerned primarily with experimental studies of visual perception. For the reader who is interested in exploring the fascinating but as yet poorly defined limits of visual awareness in chimpanzees, there are significant and provocative sources of information in the reports and films by JANE GOODALL and her husband [GOODALL, 1965], and in other writings by workers who have studied the anthropoid apes in a variety of natural and laboratory situations [MASON *et al.*, 1968; YERKES, 1943].

#### SPECTRAL SENSITIVITY

*Sensitivity in the red region.* Limits of sensitivity at the ends of the visible spectrum were carefully investigated by GRETHER, whose earlier studies of color vision in monkeys [GRETHER, 1939] indicate a considerable reduction for some primates of visibility in the red region. The chimpanzee has no such curtailed sensitivity, as is indicated in figure 1, but clearly sees as light those wave lengths at least as far into longer values as does man [GRETHER, 1940]. Under his conditions of light adaptation GRETHER found limits of 402 nm to 704 nm in three chimpanzee, captive born and aged 3 to 7 years.

These results were obtained under photopic adaptation and compared favorably with data from human observers taken under identical conditions. No scotopic absolute threshold determinations have been reported for the chimpanzee. Photopic and scotopic visibility curves for the mangabey monkey were found by BRECHER [1936] to be essentially equivalent to those of man.

*Spectral saturation values.* To what extent does the chimpanzee see narrow bands of the visible spectrum as hue, rather than white light? A wave length that is low in saturation requires more of it to be added to white in order for the mixture to be discriminated from white. By determining the energies at threshold required of each of various wave lengths, GRETHER [1941 a] measured spectral saturation curves for chimpanzee and man. His chimpanzee subjects were two males, aged 4 and 6½ years. One woman and four men served as the human subjects. For both groups of subjects, as in other classical studies, high saturation values were obtained at the two ends of the visible spectrum. These values (fig. 2) were closely comparable for all subjects. The curves were significantly different in that region between 570 nm and 575 nm, coincident with the region of lowest spectral saturation values. There was here

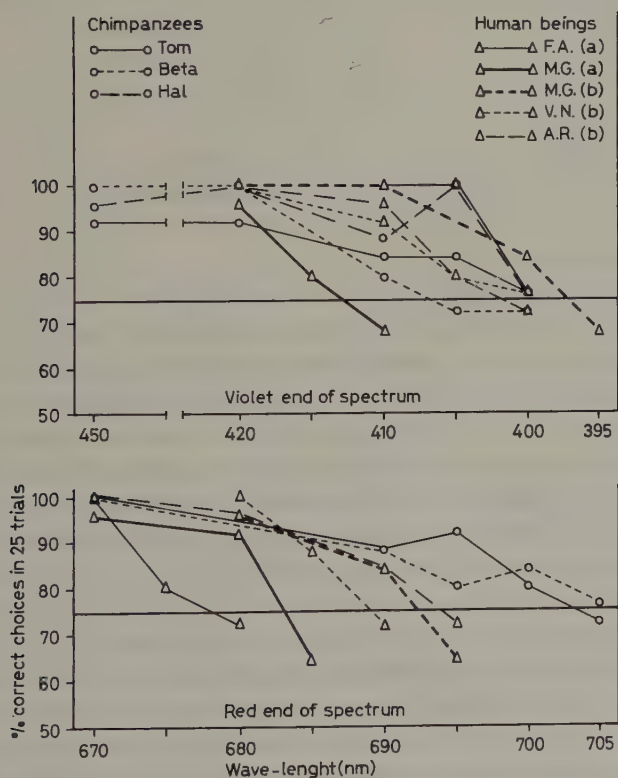


Fig. 1. Limits of spectral sensitivity in chimpanzee and man as determined under photopic adaptation [from GRETHER, 1940].

a difference in the point of minimum value of about 5 nm. Since this minimum corresponded with a shift from an experience of reddish to greenish hue by the human subjects, the assumption is made that the green and red sensitivity curves have slightly different crossover points for chimpanzees and man.

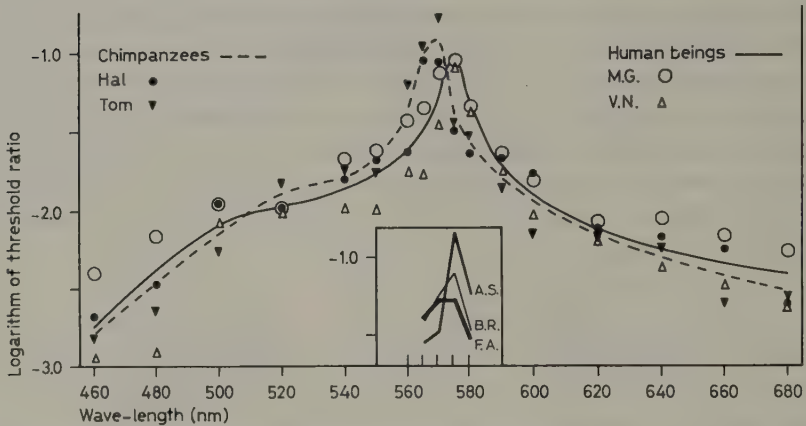


Fig. 2. Spectral saturation curves for two young chimpanzees and five adult human subjects [from GREYER, 1941a].

*Spectral hue discrimination curves.* In a further extension of his studies of color vision in primates GREYER [1940d] measured difference limens at various intervals throughout the spectrum. He found that the differential hue discrimination curve is exactly like that of man except near the long wave length end of the spectrum. This small inferiority of the chimpanzee was in agreement with a further study of hue discriminations at three selected spectral points [GREYER, 1940a]. Four chimpanzees and four human subjects were compared. No significant difference appeared between the chimpanzee and the human subjects in the blue-green region of the spectrum. However, in the yellow and the red regions, the difference limens for the chimpanzees were roughly twice those of the human subjects. The author concludes that hue discrimination in chimpanzees and in rhesus monkeys deviates slightly from that of man, and that this slight deficiency in hue discrimination could be accounted for by a less complete differentiation of the red and green receptor mechanisms. This does not in any way imply bichromatic vision in these species. They are clearly trichromats according to all criteria available.



## SIMULTANEOUS COLOR AND BRIGHTNESS CONTRAST

Contrast phenomena have been demonstrated in various animals, as also the phenomenon of transposition in brightness discrimination learning. The interesting question for investigation with the chimpanzee is whether the magnitude of these contrast effects may be different for man and chimpanzee.

After suitable training chimpanzees consistently pushed against one of the three-inch square stimulus areas. The background of each area could be independently altered. After learning to discriminate small differences, the subjects pushing on red or green in the pretraining were now presented with identical areas but provided with contrast producing backgrounds. The animals chose consistently in accordance with a simultaneous contrast effect. By determining the physical differences required to make the stimulus areas appear equal, the magnitude of the contrast effect was studied [GRETHER, 1942]. For both color contrast and brightness contrast these values were closely similar for chimpanzee and man.

COMPARATIVE MEASUREMENT OF VISUAL ACUITY  
AND FORM DISCRIMINATION

Testing human subjects and young chimpanzees of comparable age, SPENCE [1934] determined thresholds for the resolution of striations presented in horizontal versus vertical orientation. For chimpanzees aged seven to nine years, and in human Ss from five to twenty-five years of age, the thresholds for resolution were essentially similar. The data also showed comparable increases in acuity as a function of increasing brightness values. Since these were learned habits, we can safely conclude that the visual experience of man and chimpanzees reflects identical powers of edge and contour detection. On the basis of other evidence, as summarized by WALLS [1942, p.207], this general comparability may be accepted for certain of the Old World monkeys as well.

*Visual angle and retinal resolving power.* GRETHER [1941 b] has calculated from behavioral data the retinal image width corresponding to both average and lowest thresholds for chimpanzee, man, and rhesus monkey. For man and chimpanzee the highest acuity determinations both approximate a visual angle of 0.50 min. For data on the rhesus monkey the corresponding figure approximates 0.65. These values in turn when adjusted for differences in dimensions of the eye all approximate a retinal image width of 2.00 microns. GRETHER

quotes POLYAK as providing measurements of cone diameters for the fovea, representing measurements for the base of the inner cone segment. These values were actually higher for the rhesus monkey than for man and presumably for chimpanzee. In the center of the fovea cones measured from 2.3 to 3.0 microns for the rhesus monkey. The corresponding value for man was 1.5 microns. MILNER [1958] has presented the argument for not necessarily expecting a high correlation between cone diameters and acuity measurements, but obviously the size and separation of the elements of the receptor must place some limitation on its resolving power.

*Form discriminations.* Having demonstrated sufficient acuity is not the same as providing evidence for the recognition of more complex forms, or the identification of certain kinds of visual functions, such as movement or texture gradients. The experimental literature on learning in chimpanzees amply demonstrates their capacity for recognizing discrete geometric forms. They also discriminate differences in size and in proportions. Actual threshold determinations of these functions have not been made. There is clearly here a need for experimental work. That the chimpanzee has a generally high level of discriminative skills was determined by KOHTS [1923]. KÖHLER [1925] verified and extended the evidence. Mrs. KOHTS, working in Moscow, Russia, trained her young juvenile chimpanzee to match from sample. In addition to successful hue, saturation, and brightness matching, this animal accurately matched shape, size, and surface appearances of solid objects. The young home-reared chimpanzee, Viki, was also found to be quite successful in matching and in imitation behavior based upon visual perception [HAYES, 1951]. During her third year of life, Viki proved capable of imitating fairly complex action sequences with speeds and accuracies that were comparable to those of human children tested in the same situation [HAYES, 1951, pp. 183–189].

#### THE DEVELOPMENT OF FORM PERCEPTION

The newborn chimpanzee is far from possessing a mature cerebral cortex. The infant's visual behavior reflects this immaturity. Most visual responses are those mediated by midbrain oculomotor mechanisms. After birth there are immediately present indications of pupillary responses to light, optokinetic responses to the motion of striations in the visual field, and synchronous eye movements from vestibular stimulation. Single lines and isolated objects do not secure visual fixation. The development of such fixation and pursuit move-

ments of the eyes normally occurs gradually over the period of the first six weeks of life. Infants reared in diffused light or darkness fail to develop these responses until returned to a normal environment [RIESEN, 1965]. The infant chimpanzee is comparable to the human infant rather than the much more rapidly developing rhesus monkey shortly after birth [WILSON and RIESEN, 1966].

*Fixation and pursuit movements.* FANTZ [1956, 1958] has devised a technique for studying fixation preferences in very young infants. Applying this to the chimpanzee, he was able to demonstrate certain preferences for the direction of gaze in a chimpanzee infant beginning late in the second day of life. On the third day, and consistently during the first month of life, this infant showed a strong preference for looking toward a blue area rather than a red area. There was also an indication of a preference for viewing a grey circle rather than a colored line. Later, beginning on day 24, a solid model of a head secured 90% of the looking response when pitted against an oval outline form. These results testing untrained preferences provide additional evidence at an early age for visual control over orienting behavior. In view of their early age of appearance, such preferences may be accepted at least tentatively as being determined by innate neural organization.

After a few months of visual experience, a very important new dimension enters into the determination of preferences. In the infant of approximately four months and increasing thereafter, novel aspects of the environment gain predominance in determining selective fixation. When the chimpanzee infant is restricted to diffused light or very brief visual exposures during the first months of life, there is no initial novelty factor. With extensive visual experience beginning at three months or at seven months, there is a period of approximately six to eighteen weeks involved before the novelty factor becomes predominant [RIESEN, 1958, pp. 438–439]. The control of visual regard in novel stimulation has a predictable time course. As shown by WELKER [1956] and by BERKSON and FITZ-GERALD [1963], the duration of regard declines quite rapidly and consistently with successive presentations.

The early visual pursuit with eye and head movements of small objects or single lines requires several weeks to pass through the stages of what begins as a series of jerky refixations and develops into a sequence of relatively smooth pursuit movements.

Comparative data for visual regard behavioral items were obtained with infants born at the Yerkes Laboratories and tested using the Gesell Developmental Schedule (see RIESEN and KINDER [1952], for list of subjects, proce-



dures, and testing schedule). Table I presents the *critical ages* for chimpanzee and human infants. The critical ages represent approximate 50% frequency points or the age range of focal (maximum) frequencies.

*Accommodation and convergence movements.* The development of lens accommodative responses in the infant chimpanzee has received no careful investigation. We may surmise that this mechanism is absent or very poorly developed in a newborn. Convergence of the two eyes upon an object that is approaching does not occur at birth. Similarly, if an infant is raised under diffused light, this response is absent when pattern vision is first permitted. Like the movement of ocular pursuit, that of convergence begins to appear with some consistency during the second month in the normally reared animal. However, more systematic study of these visual skills is urgently called for.

After darkrearing or rearing in diffuse light, infants brought into normally patterned environments at seven months of age first showed convergence eye movements in 40 to 60 days [RIESEN, 1958].

Table I. Developmental visual regard items with their critical ages

Item	Critical ages (in weeks)	
	Ch.	Human
Supine		
64 - Stares vacantly (decreasing)	3.5	4
65 - Fixates definitely	1.5	5
Rattle		
13 - Regards examiner	2	5.5
8 - Regards spontaneously in mid-plane	4	14
11 - Regards consistently	10	23
4 - Regards after delay (decreasing)	11	15
Dangling ring		
15 - Shifts regard to E	3	6-16
6 - Disregards in mid-plane (decreasing)	5	6
20 - Follows approximately 180 degrees	6	12
1 - Regards after delay (decreasing)	8	13
22 - Follows approximately 180 degrees (r. h.)	8	5
2 - Regards immediately	9	14
21 - Follows approximately 180 degrees (l. h.)	11	14
45 - Regards dropped ring, if drops	15	25
Bell ringing		
4 - Regards examiner	7	8 (Focal)

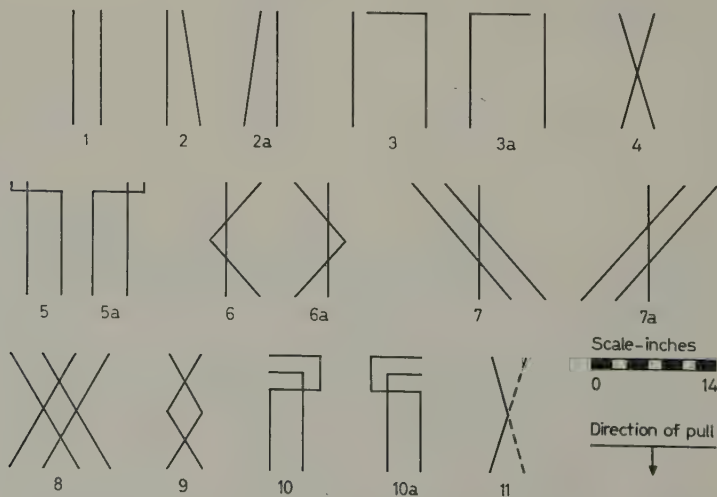
Table I. (Continued)

Item	Critical ages (in weeks)	
	Ch.	Human
Bell		
8 - Regards consistently	21	21
Massed cubes		
11 - Shifts regard	19	22
First cube		
4 - Regards after delay (decreasing)	14	L.F.
5 - Regards immediately	15	H.F.
12 - Regards consistently	24	24
Cup		
1 - Regards immediately	13	H.F.
7 - Regards consistently	22	22
Pellet		
1 - Regards (s.m.p. or n.m.p.)	12	16
5 - Regards after delay (if regards) (decreasing)	22	15
2 - Regards with definite fixation	16	18
3 - Regards (confirmed)	19	18
7 - Regards momentarily (decreasing)	20	20 (Focal)
6 - Regards immediately	21	22
10 - Regards consistently	23	26
Spoon		
2 - Regards momentarily (decreasing)	20	
6 - Regards consistently	24	22

*Perception of novelty.* The control of visual orientation by novel stimulation has been referred to above. That such novelty affects behavior other than visual fixation appears to be quite unlikely until the organism has achieved a considerable advance in cortical maturity over the newborn stage of development. A clear index of a general perceptual development, encompassing the behavior of the entire organism, is present when behavior of the infant chimpanzee is markedly aroused or inhibited by the presentation of the novel stimulus [HEBB and RIESEN, 1943]. This phase becomes highly predominant during the fourth month of visual experience. When visual experience is delayed by rearing in diffused light, the development of this discriminative behavior is correspondingly delayed. Apparently, it is valid to conclude that approximately three months is required before the organism has incorporated a recognition of the familiar in the environment. Thereafter, novel objects and

unfamiliar persons become recognized, and elicit a response of steady fixation, emotional arousal, and often an active avoidance. All, in combination, are in various degrees dependent upon the capabilities of the individual infant. Behavioral adjustment to novel stimuli takes the form of a reduction in fear with repeated exposure, followed by a heightened degree of orientation and approach. The organism then may prefer to approach the partially familiar to either the totally unfamiliar or the highly familiar [MENZEL *et al.*, 1963].

*Perceptual analysis of pattern.* A perceptual task of high order is involved in the solution of patterned string problems. This task would appear to have similar requirements for spatial pattern analysis to some of those involving the use of tools. String problems require using the correctly chosen string as a tool for securing a goal object out of reach. It is quite analagous to the using of rakes by higher primates. The series of such detour problems by KÖHLER [1925] and the patterned string problems devised by HARLOW and utilized in chimpanzees by FINCH [1941] are classical examples of the immediate visual analysis of significant spatial relationships. Feral chimpanzees tested by KÖHLER were capable of solving problems that required the use of boxes piled one



*Fig. 3.* Patterned string problems as used for comparing apes and monkeys in their capacities for visual analysis of complex patterns. Solution on a given trial requires selection of one baited string leading to the small piece of fruit attached to the distal end, which serves as reward for pulling it in. [Series adapted by FINCH, 1941, from HARLOW and SETTLAGE, 1934.]

on top of each other, the use of poles in quick climbing problem solution, and spatial detour problems. The string problem series of eleven tasks has been used with all three of the larger anthropoids. FINCH did the initial study employing four chimpanzees. The series of problems are illustrated in the accompanying figure (fig. 3). In this series, problems 6 and 7 prove rather difficult for rhesus macaques, and problems 9 and 10 were not solved [HARLOW and SETTLAGE, 1934]. FINCH [1941] found that adult chimpanzees were capable of solving the entire series, although initial errors were quite numerous on problem 1 and on the 11th problem, which he added to the series. The gorilla [RIESEN *et al.*, 1953] and the orangutan [FISCHER and KITCHENER, 1965] achieved solutions to the entire series of problems in approximately the same numbers of trials as the chimpanzees.

#### VISUAL SPACE AND VISUAL OBJECT IDENTIFICATION IN SHORT-TERM MEMORY

YERKES and NISSEN [1939] some years ago found to their astonishment that the chimpanzee, although capable of accurate memory for position in space, possesses great difficulty in the identification of objects which have appeared for viewing only a matter of some seconds earlier. One experimental procedure for studying these two types of short-term memory is known as delayed response. YERKES [1943] discovered this unique difference in the capacity for perceptual identification by pitting spatial memory against memory for the color of a particular box. We may quote his description of the procedure, as follows:

‘In each of four corners of a large room there was placed a small wooden box with hinged lid. The boxes were identical in size, shape, and surface texture, but they were painted white, black, red, and green, respectively. The chimpanzee subject was tied to a post in the middle of the room equi-distant from the boxes, while the experimenter ostentatiously put his breakfast into one of them and closed the lid. The animal was then taken away to its living quarters, and during its absence the boxes were interchanged. After a definite interval the animal was brought back and from its central position in the room given an opportunity to choose from among the boxes the one in which the food had been hidden and to approach it, and in case of correct choice take the food ... Normal human subjects ordinarily would find such a test easy to meet successfully. What actually happened in the experiment is more than surprising; it is indicative of a highly significant perceptual characteristic of the chimpanzee [YERKES, 1943, p. 104].



The results of a series of tests proved that the chimpanzee could remember *where* the box containing food had been located, but never the identification of a box by color. Subsequently, with boxes changed so that they differed not only in color but also in shape, size, and brightness, the results showed only slight improvement. With multiple differences between boxes, some success was eventually achieved by chimpanzees when delays were kept extremely short. Later work by NISSEN *et al.* [1938] confirmed the difficulty of the visual choice even in circumstances when visual object identification was not placed in direct competition with positional cues. Special training of observing responses [RIESEN, 1940; RIESEN and NISSEN, 1942] improves delayed matching and learning with delayed reward when color serves as the relevant cue.

A significant feature of the chimpanzees' perception of location and space involves the separation of critical objects to be located. Delayed response is more accurately achieved if the place of the desired object, such as food, is separated by a distance of more than 100 cm, as opposed to 26 cm. This is true even when access to the object is by a pull-in response. Here two cords that are located very close in front of the animal, and extend divergingly to each of two goal boxes, are correctly discriminated. Separating near ends of the cord by more than 100 cm is relatively little help when the objects are quite close together [NISSEN *et al.*, 1936].

When objects are discriminated on the basis of a series of learning trials, identification is facilitated if the positive member of a pair is a single item presented against a series of identical negative items. Oddity, in other words, is a feature that lends emphasis to a particular object to be identified [MC CULLOCH and NISSEN, 1937].

The use of a matching task has been referred to above in relation to the perception of complex objects. Matching on the basis of a single visual aspect of a cue is also possible in a chimpanzee. Such matching has been demonstrated for color in an experiment by RIESEN and NISSEN [1942]. This experiment also demonstrated that the identifying color could be remembered over a short delay period, the memory alone serving to identify the correct color at the moment of response.

*Short-term memory for position.* The chimpanzee apparently does not fully share with the rhesus monkey a strong dependence on frontal lobe function in the spatial delayed response performance. Where the experiments have been comparable, and the monkey suffers loss of capacity for spatial delayed response, the chimpanzee, as demonstrated by the experiments of BLUM [1949] has thus far demonstrated a good post-operative recovery of spatial delayed

response accuracy. With extensive frontal lesions ROSVOLD *et al.* [1961] found temporary performance deficits. These deficits largely disappeared several months postoperatively when the animals were retested. Recovery depended upon retraining and testing both in delayed response and in delayed alternation tasks.

We may, for our present purposes, assume that the space perceptual capacities of the chimpanzee depend primarily upon the geniculo-striate system including those peri-striate and temporal lobe areas which have repeatedly been implicated by studies of higher primates [KLUVER, 1942; CHOW, 1961]. HEBB [1949] has developed a neuropsychological theory whose basic assumptions [updated by MILNER, 1957] continue as sound working hypotheses for the examination of primate visual perception, including its developmental parameters.

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## CHIMPANZEE COLOR VISION, ACUITY AND OCULAR COMPONENTS<sup>1</sup>

D. N. FARRER and F. A. YOUNG

6571st Aeromedical Research Laboratory, Holloman AFB, NM  
and Washington State University, Pullman, WA

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### HISTORICAL INTRODUCTION

The optometric evaluation of chimpanzees was mostly speculative during the 19th Century, but shortly after the beginning of the 20th Century KÖHLER [1915] reported some preliminary (quantitative) data from his Anthropoid Station at Tenerife. He concluded that the chimpanzee had chromatic and achromatic vision, but the degree of similarity to the vision of man was still unknown. Later, KOHLER [1918] attempted to use colored paper and an electrically actuated color mixer for a red-yellow discrimination. His experimental methods, limited control of stimuli and lack of physical measurements were subject to criticism [YERKES, 1929]. YERKES and PETRUNKEVITCH [1925] summarized the earlier attempts of KOHTS [1921] to assess chimpanzee vision. Mrs. KOHTS's research involved a single chimpanzee, and the color stimuli were not

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equated for brightness. Thus, her conclusions must be considered tentative. Her method of assessment of chromatic vision (as well as recognition of planometric and stereometric stimuli) involved the learning of a somewhat complicated procedure described as 'method of choice from sample'. However, the wide range of stimuli presented in counter-balanced order and sequence lend support to YERKES [1929] conclusions that 'the chimpanzee possesses two sorts of visual sensitiveness, the nonchromatic and the chromatic ...'

In a series of precise experiments, GREYER [1940a, 1940b, 1940c, 1940d, 1940e, 1941a, 1941b, 1941c, 1942] attempted to quantify the color vision capacities of the chimpanzee. Hue discrimination and limits of spectral sensitivity were obtained with monochromators which incorporated single filament lamps and prisms focusing on 2.25-in windows. Four chimpanzees (varying in age from 3 years to 7 years) were extensively tested, and it was concluded that photopic hue discrimination in chimpanzees and humans is approximately equal in the blue-green region of the spectrum but the difference limens for chimpanzees are almost double the humans' difference limens in the yellow and red regions. Also, the spectral limits for light adapted humans and chimpanzees were almost identical. The color vision of the chimpanzee was so much like man that it was concluded that it is most probably a trichromatic sensory system. Using apparatus which allowed the independent manipulation of hue, brightness and saturation, it was concluded that simultaneous contrast effects are approximately the same magnitude in chimpanzees and man. Under contract to Aeromedical Research Laboratory, KLOPFER and YOUNG [1967] developed apparatus and tested both spectral sensitivities and brightness functions in three chimpanzees. Their data essentially support the earlier findings of GREYER. However, emphasis was placed on intersubject variability. Comparing the primate data to data obtained from humans in the same test situation, minor differences were reported in sensitivity to the long wave lengths and maximum sensitivities.

#### REFRACTIVE CHARACTERISTICS

The capacity of chimpanzees to resolve fine detail in their field of view was systematically studied by SPENCE [1934]. The technique which SPENCE used involved two modified Ives instruments, each mounted above a food tray located 72 centimeters from the subject's eyes. Each trial was initiated by lifting an opaque screen in front of the experimental cage, exposing the two Ives stimuli, food trays and ropes. Food was obtained by pulling the rope attached

to the food tray under the homogeneous stimulus. Pulling the rope attached to the food tray under the striated stimulus terminated the trial without a food reward. Thus, the striated-homogeneous discrimination test allows the determination of minimal separable visual acuity. This method is an attempt to determine the refractive status of the eye by the use of subjective criteria. All techniques which require discrimination learning and subjective responses for the approximation of the refractive status of nonhuman primate eyes are very time consuming, and as a result, the number of animals tested is always necessarily small. Although published reports of nonhuman visual acuity experiments do not mention original training time required to obtain these data, experience in our own laboratory indicates that 90 to 120 days of one hour per day per rhesus monkey is required.

Since our original research objective was to examine each chimpanzee eye each year for a longitudinal study of the changes in their refractive characteristics, the subjective visual acuity procedure was not practical.

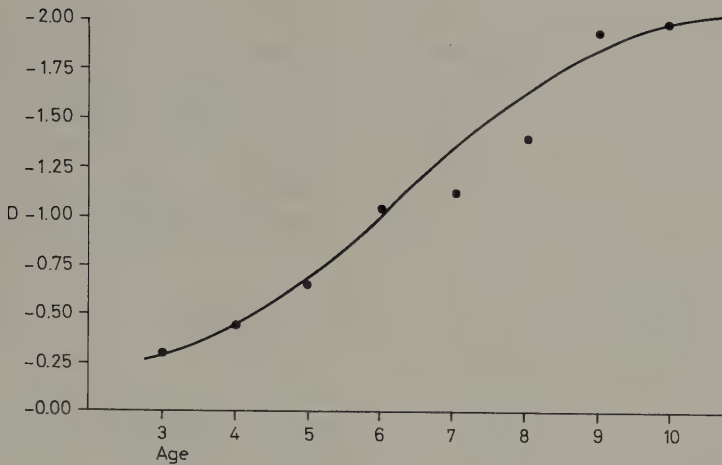
Thus, the retinoscopic procedure was selected. This procedure does not require a learned response, and it requires less than five minutes for the refraction *per se*. The retinoscopic procedure was described in the 1860's, and by 1873 retinoscopy was established as a method for determining refractive error. In 1936, COPELAND published a paper on a simplified method of streak retinoscopy which is a commonly accepted method in clinical practice, and it was the method employed in this study.

It should be noted that a zero refractive error determined retinoscopically does not guarantee normal visual acuity. That is to say, they are not equivalent techniques.

As mentioned previously, the purpose of the present study was to determine the refractive error of each chimpanzee eye, and to re-examine each eye annually.

The retinoscopic data which have been collected during the last six years are shown in figure 1. This graph shows the relationship between the age of the chimpanzees and the amount of refractive error in diopters. The check on the agreement between the two refractionists was accomplished by a product moment correlation coefficient which indicated a positive correlation of 0.93. This value is statistically significant beyond the 0.01 confidence limit.

Mostly, these data represent the same animals tested each year. Unfortunately, all chimpanzees are not available each year and some new chimpanzees are added to the colony each year as the colony grows in size. The one major conclusion drawn from these data is that these growing chimpanzees are progressing toward myopia as they continue to live in the colony environment.



*Fig. 1.* The progression of myopia as a function of age.

Also, it should be noted that this graph is composed of all the data without regard to length of time the chimpanzee was in the colony, but these data reflect a trend toward myopia.

These data pose one additional hazard to interpretation: Inter and intra subject variability are confounded. First, each chimpanzee contributed two eyes to the data although the same results are obtained when only the right eye is used. Second, chimpanzees stay a varying length of time in the Holloman Colony. Hence, some animals have been tested every year since the project was initiated in 1962, while others are tested less often.

The future plans for this long term research program necessarily involve two directions.

First, the 6571st Aeromedical Research Laboratory at Holloman AFB has a 30-acre outdoor housing facility for a small group of chimpanzees which should provide control data bearing on the question whether it is the colony environment which enhances the progression of myopia.

Second, a few chimpanzees must be selected for training on the subjective visual acuity test. The correlation between estimations of refractive error made by retinoscopic methods and subjective methods is very high for human subjects showing varying degrees of myopia – but this correlation has not yet been determined for the chimpanzee. For example, HIRSCH [1945] found a correlation of +0.95 between the logarithm of visual acuity and the logarithm of the degree of myopia. He also worked out a prediction equation which permits



the prediction of visual acuity from the refractive error. KEMPE, COLLINS and JARMAN [1928] found correlations of  $+0.41$  between visual acuity and refractive error in their total population while the myopic children had a correlation of  $-0.80$  between the same measures. YOUNG [1959] found comparable values of  $+0.60$  and  $-0.84$  for the relationship between visual acuity and refractive error when the actual scores are used rather than log scores. In any case it is clear that the correlation between visual acuity and refractive error is much higher in myopic subjects than it is in an unselected population.

In the use of chimpanzees for visual research the low correlation between visual acuity and refractive error may not be detrimental since the investigator in many cases is interested in determining whether the animal has normal visual acuity. Any animal which has a refractive error between  $+2.00$  and  $-0.50$  diopters as determined by retinoscopy under cycloplegia and has no obvious retinal pathology as determined by ophthalmoscopy under similar conditions, should have normal (20/20) acuity at far unless it demonstrates obvious visual behavior difficulties. The animal should also have good acuity at near provided it is not old enough to suffer from presbyopia.

#### OPTICAL CHARACTERISTICS

The development of photographic ophthalmophakometry and its application to the study of the human primate eye permits the determination of the power of the front and rear surfaces of the lens of the eye. The application of ultrasonic measurement techniques to the eye permits determination of the thickness of the lens, depth of the anterior chamber and of the vitreous chamber. When these measures are supplemented with an objective, cycloplegic retinoscopy and a clinical keratometric examination, the basic components of ocular refraction can be calculated. Since these techniques are equally applicable to the subhuman primate eye, it is possible to measure the ocular characteristics of chimpanzees. The optical characteristic of the chimpanzees is based upon one hundred chimpanzee eyes. The chimpanzee population was obtained in part at the Yerkes Regional Primate Research Center but most of the chimpanzee population has been followed for a number of years at Holloman Air Force Base, New Mexico. In the case of the Holloman population it was possible to identify age quite accurately since the animals had been observed for as long as seven years. However, with the Yerkes population the age could only be estimated and was not actually used in the present analysis. The chimpanzee population ranged between two years and sixteen and a half years of age.

All measurements were originally intended to be based upon the right eye only. The right eye was selected since it is generally the dominant eye and usually has characteristics which are somewhat different than those of the left or nondominant eye. Unfortunately, a sufficient number of right eyes were not available to make up the total originally desired. Thus, of the one hundred chimpanzee eyes, three are left eyes.

All animals were measured under anesthesia induced by 0.75-mg phen-cyclidine hydrochloride (Sernylan) per kilogram of body weight given intramuscularly or an amount required to produce a comparable level of anesthesia given intravenously. All subjects had 2% cyclopentolate hydrochloride (Cyclogyl) as needed to induce cycloplegia. The cycloplegic was administered to each eye (two drops) for three administrations spaced ten minutes apart. Measurements were made between forty and ninety minutes after the first drop. The apes were strapped to hydraulic chairs which could be adjusted to any position. The refractions were performed with a retinoscope and trial case lenses. The animals' eyelids were held open by means of an infant speculum.

The ultrasound measurements were made with a Tektronix type 547 oscilloscope and a Nortec Model NDT-100 plug-in sound source supplying a hand-held probe fitted with a 3-cm water-filled extension tube which had an internal diameter of 6 mm. The end of the extension tube was covered by a piece of Saran Wrap which made contact with the cornea of the eye. The trace on the oscilloscope was photographed and measured with a two dimensional microscope. The film distances were converted into eye distances using procedures described in detail elsewhere [YOUNG, LEARY and FARRER, 1966].

The results are presented in table I separately for males and for females. Generally those values indicated as powers were determined from the phakometry results except for the corneal power which was measured directly with the keratometer. Those measures indicated as depths, lengths, or thicknesses involving millimeters were determined from ultrasonography. One point of interest is the relationship between the axial length of the eye and refractive characteristics of the eye. There is a relatively high correlation between refractive error and axial length for chimpanzees of  $-0.86$ .

As indicated earlier many chimpanzees in the laboratory environment develop myopia and the course of development appears to be similar to that found in humans. An attempt [YOUNG and LEARY, 1968] was made to compare these developmental sequences by matching 50 human and 50 chimpanzee eyes which either changed from hypermetropia or emmetropia to myopia or from lower to higher levels of myopia during comparable time periods of longitudinal studies on humans and chimpanzees. The matching was based

*Table I.* The means and standard deviations, together with the ranges, for the different refraction groups combined

Subjects	Measure	Age (yrs)	Vert. Ocul. Refraction (diopters)	Corneal Power (diopters)	Depth Ant. Chamber (mm)	Front Lens Power (diopters)
Males						
Chimpanzee	Means	7.0	0.0	47.2	3.8	8.8
	SDs	2.68	2.31	1.53	0.31	1.59
	Range	9.0	+4.0 to -7.8	7.6	1.7	9.6
	N	50	50	50	50	50
Females						
Chimpanzee	Means	7.25	0.0	48.0	3.7	9.1
	SDs	3.19	2.63	1.79	0.32	1.26
	Range	14.6	+5.4 to -7.7	6.8	1.4	6.6
	N	50	43	50	50	50

Lens Thickness (mm)	Back Lens Power (diopters)	Equiv. Lens Power (diopters)	Equiv. Total Power (diopters)	Length of Post. Seg- ment (mm)	Axial Length (mm)
Males					
3.6	16.2	24.7	66.8	14.5	21.9
0.19	3.83	2.96	1.86	0.22	0.29
0.7	14.4	11.6	7.3	3.4	20.8 to 24.1
50	50	50	50	50	50
Females					
3.6	16.8	25.5	68.0	14.3	21.5
0.19	3.75	3.48	2.72	2.06	0.90
0.7	14.1	14.0	11.5	5.0	20.1 to 23.2
50	50	50	50	50	50

on developmental age, sex, initial refractive error and time interval between follow-up. The age matching could be achieved, but the sex matching was not possible since the proportions of males and females were reversed in the two groups. Further, the chimpanzees demonstrated higher levels of myopia than

the human subjects which made it difficult to match the groups in terms of initial and final refractive characteristics. All comparisons were made in terms of annual rate of change in both groups for all components. All measurement conditions were similar for the humans and chimpanzees except that the chimpanzees were under an anesthetic, Sernylan.

There was good agreement within age levels and by sexes between humans and chimpanzees. The only major difference occurs in the direction of change in vertical corneal power, since in human subjects this decreases with increasing age while it tends to increase with age in the chimpanzee. Since all measurement conditions were the same for corneal measurement, this difference is probably not due to the measurement conditions. The cornea of the chimpanzee appears to be more edematous than that of the human. This condition may be a reaction to the great amount of foreign matter introduced by the animal's fingers. It is possible that the difference between the changes in the human and the chimpanzee corneas is related to this condition which appears to be more common in older animals. The higher incidence of corneal ulcers in older animals lends support to this hypothesis.

When the annual rates for various powers are compared, specifically, we find that the vertical ocular refraction rate of change is approximately the same for both humans and chimps but there is more variability in the chimpanzees than in the humans.

The vertical corneal power change decreases in the human but increases in the chimpanzee and again with greater variability in the chimpanzee.

The rate change of the lens power at the corneal vertex decreases in both groups but by a greater amount in the chimpanzee with consistently higher variability in the chimpanzee.

The power of the eye at the corneal vertex decreases in both groups but by a greater amount in the chimpanzee and again, with higher variability.

Reduced axial length decreases in both groups with roughly comparable amounts but more variability in the chimpanzee.

With respect to the annual rate of changes of length, the depth of the anterior chamber, the length of the posterior chamber and the axial length increased in both humans and chimpanzees by approximately the same amounts with approximately the same degree of variability. The lens thickness decreases in humans but tends to remain relatively stationary in chimpanzees with slightly higher variability in the chimpanzee than in the human. There is a close correlation between the increase in posterior chamber length and the increase in axial length with a correlation of 0.97 in the chimpanzee and 0.93 in the human.



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Authors' address: DONALD N. FARRER, Ph.D., 6571st Aeromedical Research Laboratory, *Holloman AFB, NM* (USA); FRANCIS A. YOUNG, Ph.D., Washington State University, *Pullman, WA* (USA).

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## MORPHOLOGY OF THE CHIMPANZEE KIDNEY: A COMPARISON WITH MAN

C. CRAIG TISHER

Department of Metabolism, Division of Medicine  
Walter Reed Army Institute of Research, Washington, DC

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## I. INTRODUCTION

The present chapter will deal with the light microscopic and electron microscopic morphology of the chimpanzee (pan) kidney. An introduction to the gross anatomical features appears elsewhere in this volume (chapter 'Renal function in the chimpanzee') and therefore will not be covered in the present section except when necessary to describe more clearly the various light and electron microscopic features of this organ. When possible, the findings in the chimpanzee will be compared with similar anatomical observations which have previously been described in the human kidney [43, 44, 4, 32, 49, 52, 9, 8, 3, 11, 26, 48, 17, 20, 21, 22, 23]. Finally, where information is available, structural functional relationships will be reviewed for the various components of the nephron.

The material to be described represented both kidneys from a young female chimpanzee weighing 24 kg and percutaneous renal biopsies from two other young (3 and 5 years old) chimpanzees. None of the animals had evidence of renal disease and were otherwise well and healthy.

## II. GROSS OBSERVATIONS

On sagittal section the thickness of the renal cortex varies from 10 to 13 mm, appearing slightly thicker at the upper and lower poles. There is no obvious separation of the cortical region into inner and outer zones. The medulla is approximately 18–20 mm in thickness, again being slightly longer from corticomedullary junction to the papillary tip when measured at the upper and lower poles. The medulla can be divided into an outer medullary zone meas-



uring approximately 10–11 mm in thickness and an inner medullary zone of 7–9 mm. The papillary tip is somewhat flattened and covered with transitional epithelium which thins slightly at the fornix of the renal pelvis, but again increases in thickness when reflected over the wall of the pelvis.

### III. RENAL CORPUSCLE

As suggested by TRUMP and BULGER [49], the term renal corpuscle will be used in place of the term glomerulus to designate that portion of the nephron which includes: 1. the capillary network lined by endothelial cells; 2. a central region of mesangial cells with contiguous mesangial matrix material; and, 3. visceral and parietal layers of epithelial cells and their associated basement membranes, the latter more familiarly termed Bowman's capsule.

#### A. Light Microscopy

The renal corpuscle of the chimpanzee kidney resembles that of most other mammals and is composed of three main cell types which are easily distinguishable by their position and peculiar staining characteristics. These include the mesangial or 'stalk' cells which lie in the intercapillary or mesangial region, the endothelial cells which line the capillary loops, and the epithelial cells that cover Bowman's capsule and reflect onto the external surface of the peripheral basement membrane of the capillary loops (fig. 1). The latter

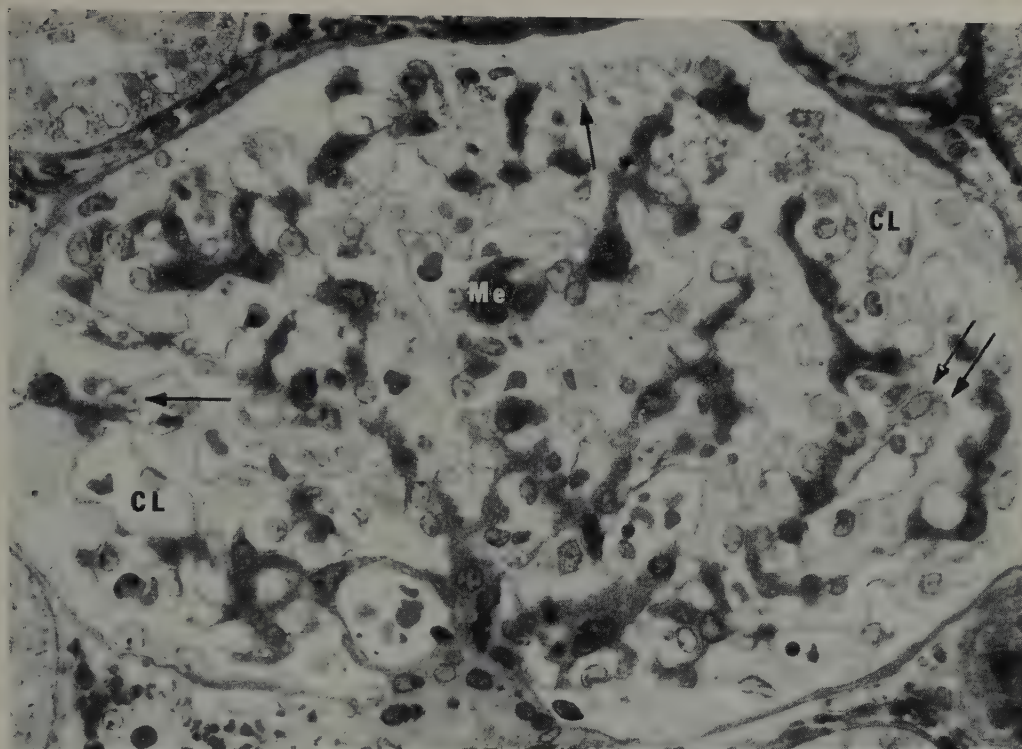
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*Fig. 1.* Photomicrograph of a renal corpuscle from a non-diseased chimpanzee kidney. The capillary lumens (CL) are patent and contain red blood cells. The mesangial cells (Me) are dark-staining while the endothelial cells (arrow) and visceral epithelial cells (double arrow) are pale staining.  $\times 535$ .

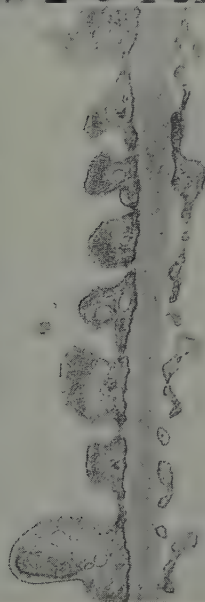
*Fig. 2.* Electron micrograph of the peripheral capillary loop of a renal corpuscle. The foot processes of the visceral epithelial cells are shown on the left and the attenuated endothelial cytoplasm is present on the right of the basement membrane. From left to right the three layers of the basement membrane include the *lamina rara externa*, the *lamina densa*, and the *lamina rara interna*.  $\times 14,400$ .

*Fig. 3.* Electron micrograph of a portion of a peripheral capillary loop showing the marked irregularity of the *lamina densa* and *lamina rara interna*. Finger-like extensions of the basement membrane are occasionally noted (arrow).  $\times 19,775$ .

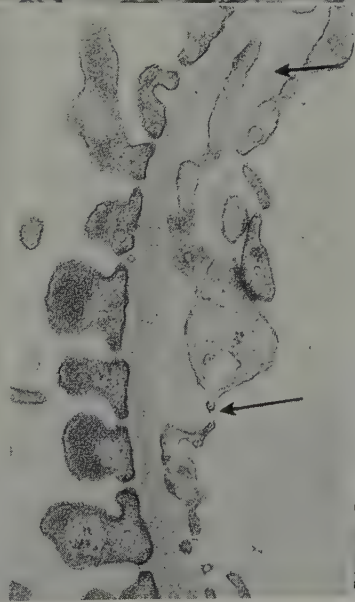
*Fig. 4.* Electron micrograph of the capillary basement membrane (Bm) dividing at the 'waist' region adjacent to the mesangial cell (Me). See text for explanation. En, endothelial cell; CL, capillary lumen.  $\times 10,100$ .



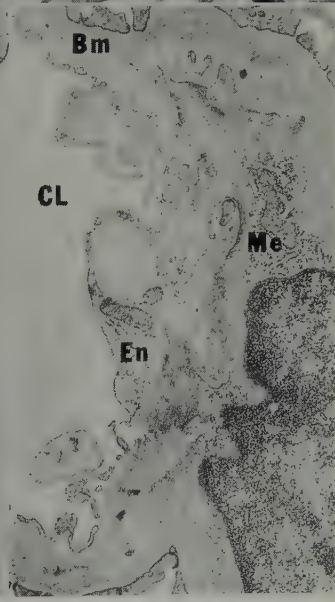
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cell type is subdivided into parietal epithelial cells and visceral epithelial cells. On 0.5–1.0  $\mu$  sections cut from Epon-embedded tissue [29], and stained with toluidine blue [51], the mesangial cell nuclei are dark in appearance and surrounded by dense blue staining material, the mesangial matrix. With the periodic acid-Schiff (PAS) stain the mesangial matrix material surrounding these cells stains positively. In contrast, the endothelial cells situated within the capillary loops adjacent to the mesangial cells stain lightly with toluidine blue and are not PAS-positive on paraffin sections. The parietal epithelial cells line Bowman's capsule and are squamous to low-cuboidal in appearance. The visceral epithelial cells actually lie within Bowman's space and extend foot processes to one or more nearby capillary loops.

As in the human, an afferent arteriole enters the renal corpuscle at the hilus and divides into several capillaries which reform in the same region and exit as the efferent arteriole.

### B. Electron Microscopy

1. *Basement membrane.* The basement membrane of the peripheral capillary loop is composed of three layers which includes the *lamina rara interna* nearest the vessel lumen, the *lamina densa*, and the *lamina rara externa* (fig. 2). In the chimpanzee the approximate thickness of the basement membrane is 2,200 Å. The peripheral portion of the capillary loop varies considerably in thickness, largely due to localized thickening of the *lamina densa* and secondarily of the *lamina rara interna*. This results in a very irregular configuration on the endothelial surface of the basement membrane (fig. 3). Near the mesangium the basement membrane divides and a portion of it becomes continuous with the matrix of the mesangial cells (fig. 4).

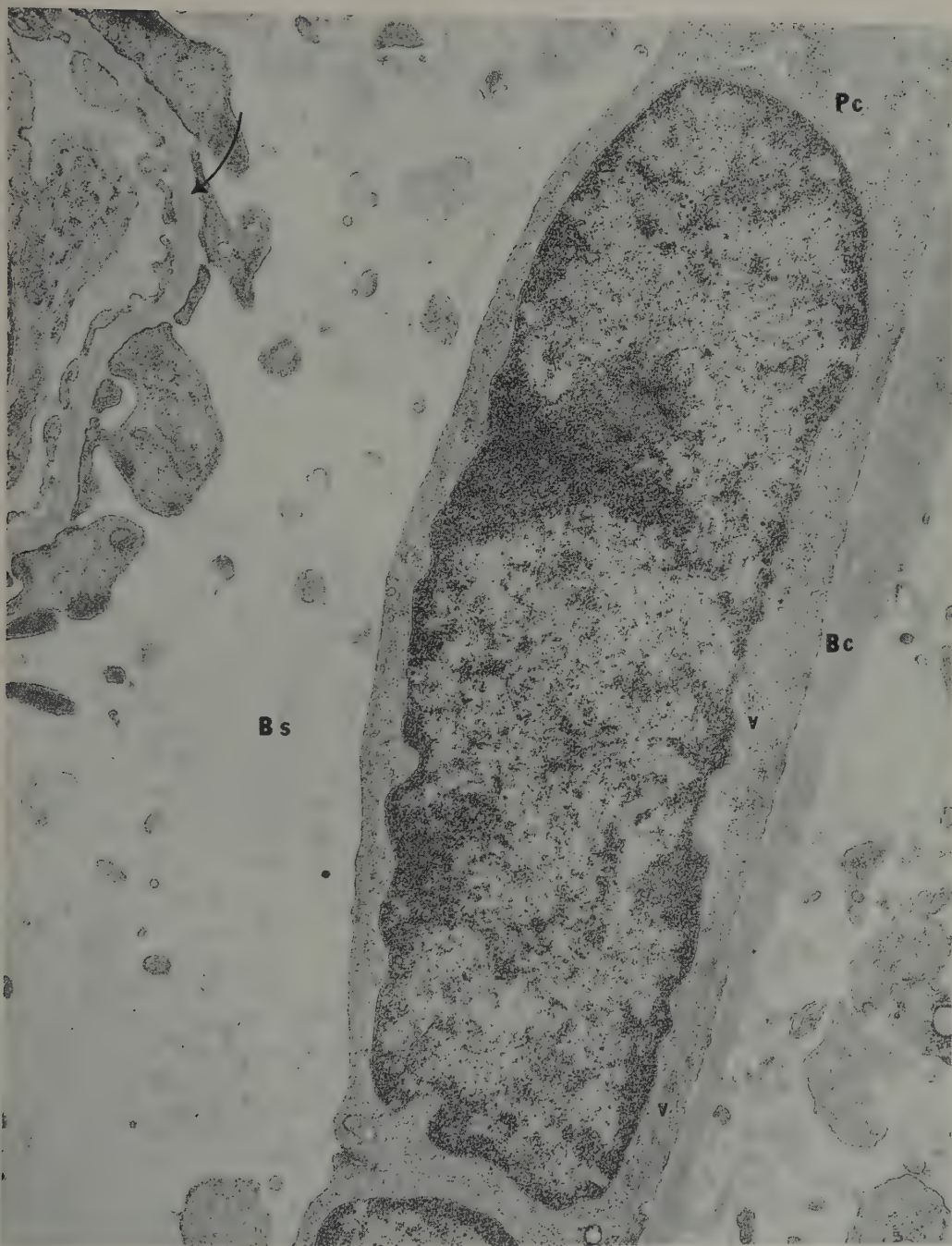
Rarely, well localized finger-like extensions of the basement membrane invaginate the overlying endothelial cell cytoplasm (fig. 3). At the vascular pole or hilus of the renal corpuscle the capillary basement membrane is continuous with the basement membrane of Bowman's capsule.

2. *Epithelial cells.* Two distinct types of epithelial cells, visceral and parietal, are present within the renal corpuscle. The parietal epithelial cells line Bow-

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Fig. 5. Electron micrograph of parietal epithelial cell (Pc) lining Bowman's capsule (Bc). Bs, Bowman's or urinary space; peripheral capillary loop (arrow); v, vesicles (see text for explanation).  $\times 15,200$ .







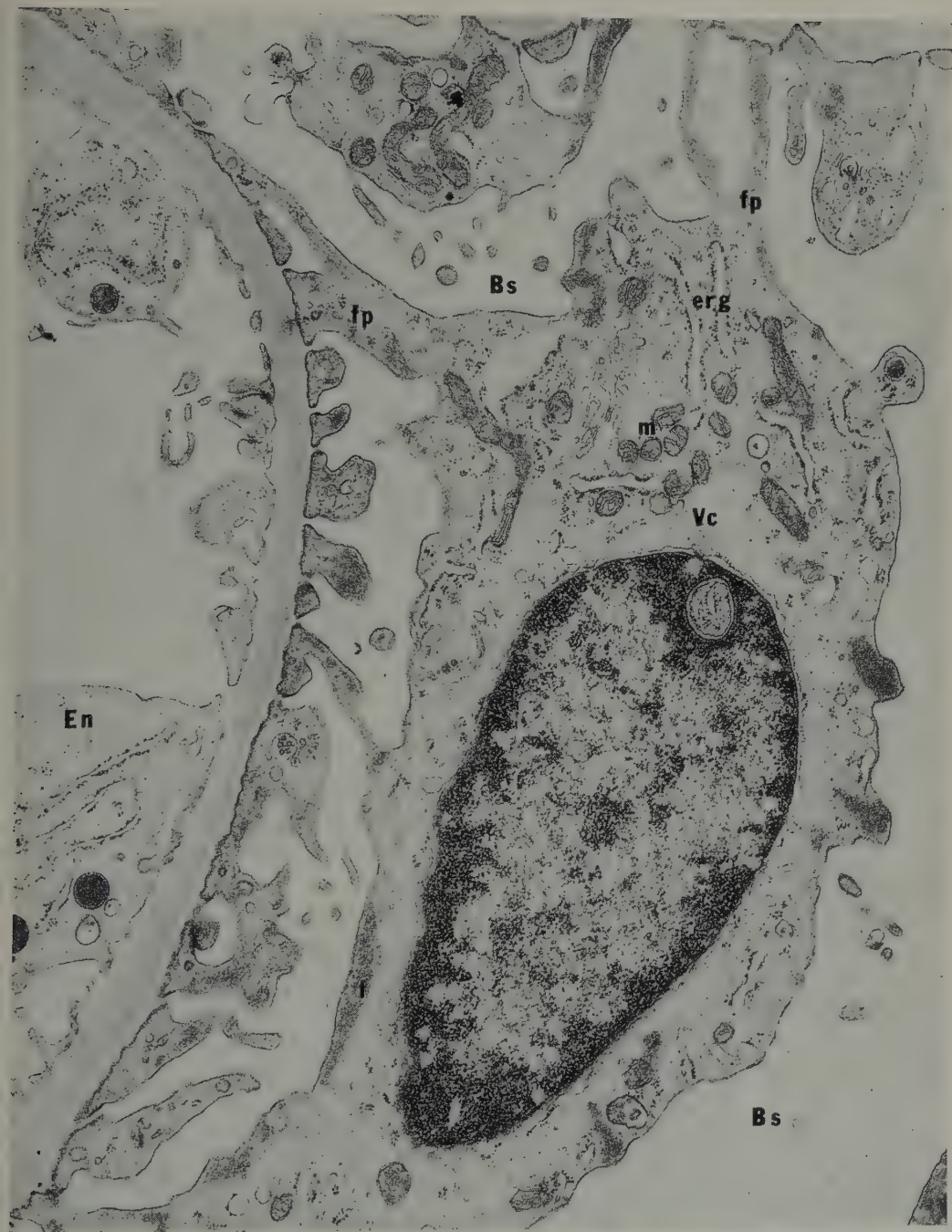
man's capsule and are of the simple squamous to low cuboidal type. Organelles within these cells include mitochondria, endoplasmic reticulum, inclusion bodies (cytosomes), lipid droplets, and the Golgi apparatus (fig. 5). Large bundles of fine filaments or fibers are commonly observed coursing through the cytoplasm of these cells. In addition, large numbers of small vesicles, resembling the pinocytotic vesicle within blood vessels as first described by PALADE [35] were commonly observed along the cell membrane surfaces. These cells occasionally form complicated intercellular relationships with adjacent cells. At the vascular pole or hilus they reflect onto the peripheral capillary basement membrane and become the visceral epithelial cells. At the urinary pole there is an abrupt transition from the simple squamous epithelial cell to the infinitely more complex tall columnar cell characteristic of the proximal tubule.

The visceral epithelial cells or podocytes cover the external or urinary space surface of the peripheral capillary basement membrane. Numerous foot processes extend as finger-like projections from the main body of the cell to come into direct contact with the *lamina rara externa* of the basement membrane (fig. 6). One cell often comes into contact with more than one capillary loop by virtue of its foot processes. Within the main portion of the visceral epithelial cell cytoplasm are abundant quantities of rough-surfaced endoplasmic reticulum. Multivesicular bodies are the most common inclusion body present within these cells and are often found in the individual foot processes adjacent to the peripheral capillary basement membrane (fig. 6). Cytosomes are frequently observed and Golgi complexes and mitochondria are abundant. The bundles or strands of dense-staining filaments, similar to those observed within parietal epithelial cells, are numerous in the visceral epithelial cells and often extend into the foot processes (fig. 6). Foot process 'fusion' over short segments of the peripheral capillary loops is commonly observed. Qualitatively this foot process 'fusion' is similar to that seen in various proteinuric states.

3. *Endothelial cells.* The endothelial cells which line the inner surface of the basement membrane of the capillary loops and come into intimate contact with the *lamina rara interna* are not greatly different from endothelial cells

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Fig. 6. Electron micrograph depicting a typical visceral epithelial cell (Vc) with foot processes (fp) extending toward two different peripheral capillary loops to come into contact with the *lamina rara externa*. En, endothelial cell; Bs, Bowman's space; f, filaments; erg, rough-surfaced endoplasmic reticulum; m, mitochondrion.  $\times 15,800$ .



lining other vessels. The main portion of the endothelial cell including its nucleus is usually situated adjacent to the mesangial region opposite the most peripheral portions of the capillary loop (fig. 7). Here the cell bulges into the capillary lumen, but in all other regions the endothelial cytoplasm is greatly attenuated. Multivesicular bodies are the most frequent inclusion body observed in these cells, although cytosomes are present. Endoplasmic reticulum and mitochondria are also observed within endothelial cells. Small pores termed fenestrae are a common feature of these cells. The endothelial cell cytoplasm appears to be quite susceptible to the rigors of tissue preparation and bleb-like swellings and protrusions into the capillary lumen from the endothelial cell surface are a common occurrence in tissue obtained by biopsy.

4. *Mesangial cells.* These cells sometimes termed 'stalk' cells form the mesangium of the renal corpuscle. They occupy a central location which probably relates to one of their suspected functions, that of support for the renal corpuscle (fig. 7). These cells are abundant in matrix material which is similar to that of the peripheral capillary basement membrane. The cells contain inclusion bodies or cytosomes and abundant quantities of rough-surfaced or granulated endoplasmic reticulum.

Frequently, processes extend from the mesangial cells outward into the capillary lumen where they may come into direct contact with the contents of the vessels. More often, however, they are covered by the overlying endothelium (fig. 7).

### *C. Comparison with Human*

In most respects the renal corpuscle of the chimpanzee kidney is nearly identical to that of the human. The cellular components are the same. The sub-cellular organelles within the individual cell types are similar both qualitatively and quantitatively. The only possible exception to this finding may be found in the visceral epithelial cells. In the chimpanzee, multivesicular bodies are more prominent and are commonly observed in the individual foot processes of the visceral epithelial cells. Also within the visceral epithelial cells

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*Fig. 7.* Electron micrograph showing the intimate relationship between a mesangial cell (Me) above and an endothelial cell (En) below. Processes (p) of the mesangial cell extend toward the capillary lumen (CL) and invaginate the overlying endothelium. C, cytosome; erg, rough-surfaced endoplasmic reticulum; Mm, mesangial matrix material; Bs, Bowman's space.  $\times 13,550$ .







of the chimpanzee renal corpuscle, bands or clumps of dense filaments are very common and are present in a much greater degree than in the human. They often extend down into the individual foot processes adjacent to the basement membrane.

The basement membrane of the chimpanzee renal glomerulus is similar in structure to that of man. However, it is not as thick, measuring approximately 2,200 Å, whereas in the human the basement membrane has been found to measure approximately 3,288 Å [23]. The chimpanzee basement membrane is extremely variable in thickness and often exhibits fusiform as well as localized thickening.

There appears to be more evidence of foot process 'fusion' of the visceral epithelial cell in the chimpanzee than in man. What the significance of this observation may be is unknown. These animals were free of proteinuria, a condition in which foot process 'fusion' is common.

#### *D. Structural-Functional Correlation*

The renal corpuscle is responsible for the production of a glomerular filtrate, probably by a process of ultrafiltration. Specific roles related to the overall function and maintenance of the renal corpuscle appear to be assigned to its various components. In the process of filtration the endothelial cell represents the first barrier. FARQUHAR, WISSIG and PALADE [12] have shown experimentally that small molecules such as ferritin which has a diameter of approximately 100 angstroms, pass easily through the fenestrae or pores of the endothelium. Larger molecules such as globin are apparently transported

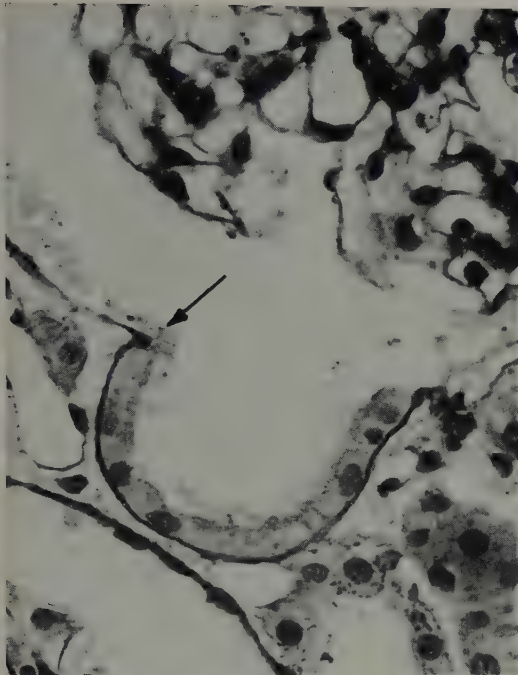
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*Fig. 8.* Photomicrograph depicting the abrupt transition (arrow) from the lowlying squamous epithelium lining Bowman's capsule of the renal corpuscle to the tall columnar cells typical of the initial or 'neck' region of the proximal tubule.  $\times 540$ .

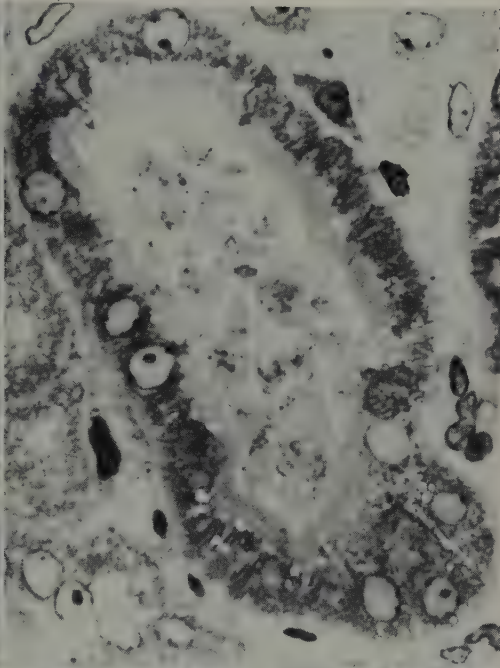
*Fig. 9.* Photomicrograph showing the typical appearance of the *pars convoluta* region of the proximal tubule. The tubular lumen is filled with cellular debris (see text for explanation). Note the elongate mitochondria and numerous apical vacuoles within the individual cells. This tissue was obtained by percutaneous biopsy.  $\times 790$ .

*Fig. 10.* Photomicrograph of two adjacent *pars recta* segments of the proximal tubule. This tissue was fixed by intravascular perfusion with formalin and as a result the tubular lumens are patent and largely free of cellular debris.  $\times 585$ .

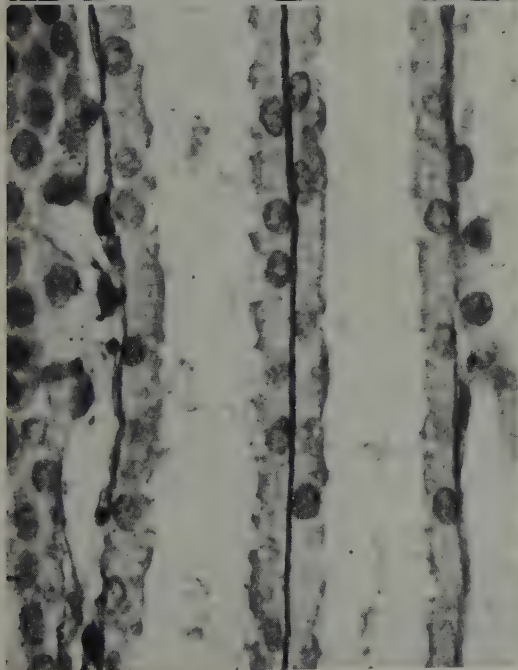
*Fig. 11.* Photomicrograph demonstrating the gradual transition from the *pars recta* (PR) segment of the proximal tubule above, to the low-lying squamous epithelium characteristic of the early descending thin limb of Henle (TL) below. The arrow denotes a typical thin limb cell within the terminal *pars recta* segment.  $\times 630$ .



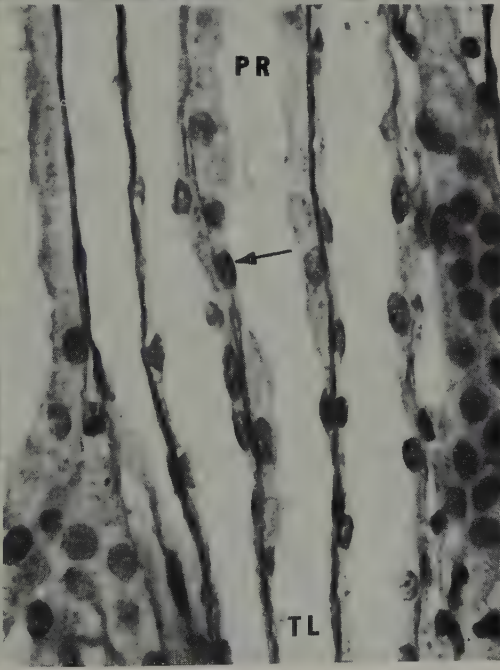
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mainly through the endothelial cells as observed by MENEFEY, MUELLER, BELL and MYERS [31]. The exact role of the basement membrane in the production of an ultrafiltrate is unknown. It does not, however, represent a significant barrier to the passage of relatively large molecules such as globin [31].

The final obstacle to the movement of the glomerular filtrate from the capillary to the urinary space is the visceral epithelial cell and its numerous foot processes. It has been suggested by FARQUHAR, WISSIG and PALADE [12] that these cells may act to monitor glomerular filtration but definite proof of such a role is lacking. There is increasing evidence, however, that the visceral epithelial cells act to synthesize and maintain the *lamina rara externa* of the peripheral basement membrane [25, 12, 48, 1].

The mesangial cell appears closely related to smooth muscle cells. Under certain conditions these cells produce granules presumably containing renin. The studies of FARQUHAR, WISSIG and PALADE [12] and LATTA, MAUNSBACH and MADDEN [27] indicate these cells are capable of phagocytosis. The presence of acid phosphatase activity within mesangial cells, ROSEN and TISHER [39] indicates that these cells probably have the necessary enzymatic activity to participate in cellular digestion of ingested materials (endocytosis). JØRGENSEN [20] and TRUMP and BULGER [49] have observed processes of these cells extending through the overlying endothelium into the capillary lumen presumably in their role as phagocytes.

#### IV. PROXIMAL TUBULE

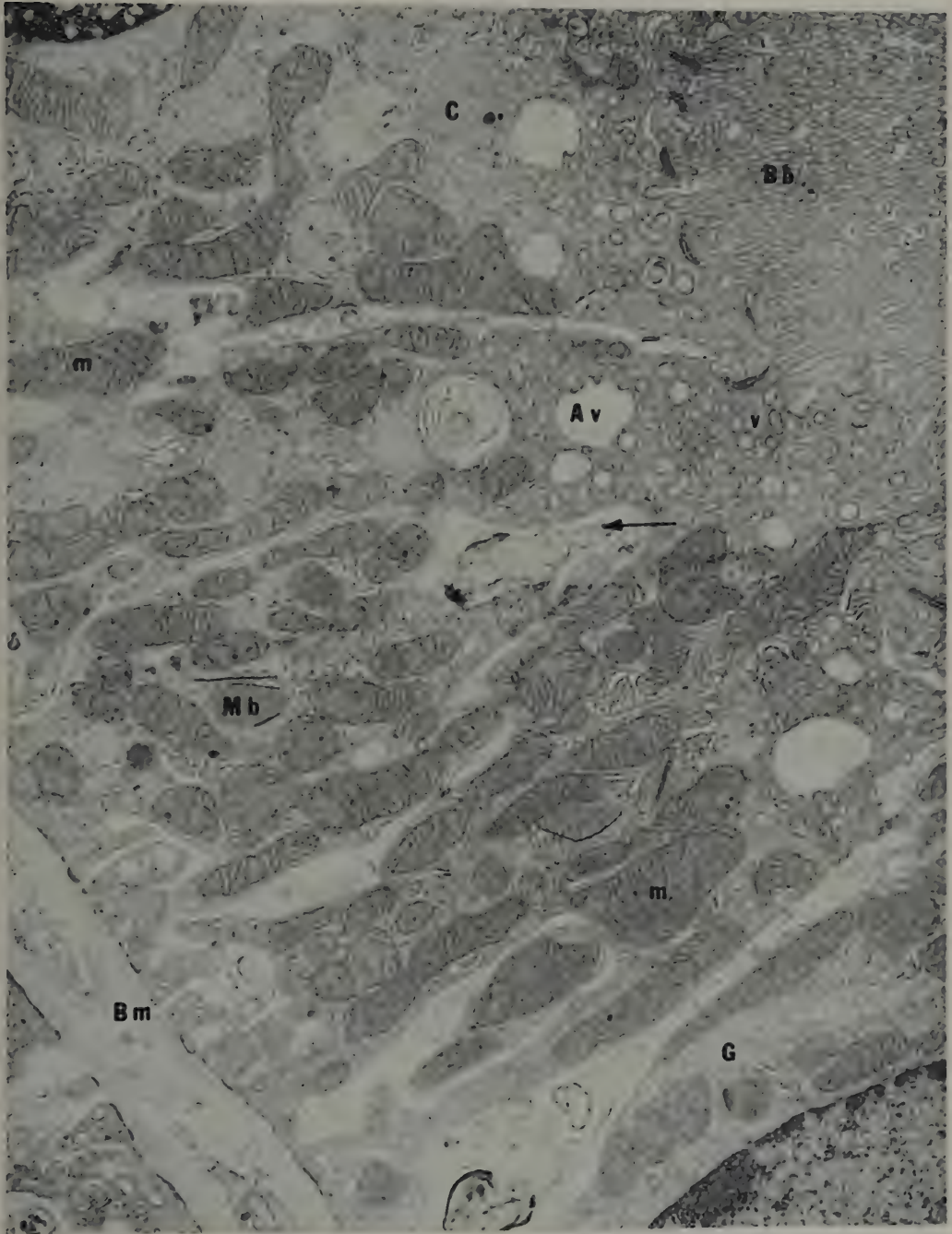
##### *A. Light Microscopy*

Four distinct regions of the proximal tubule can be identified within the chimpanzee kidney. These include the initial or 'neck' region, the convoluted portion or *pars convoluta*, the straight descending portion or *pars recta*, and the transition region from the terminal *pars recta* into the thin descending limb of Henle. From initial observations it appears likely that there are actually three distinct segments of the chimpanzee proximal tubule excluding the two transition regions. This segmentation is similar to earlier findings

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*Fig. 12.* Electron micrograph of a typical proximal tubule cell characteristic of the neck and *pars convoluta* segments. See text for description. Bb, brush border; C, cytosome; Mb, microbody; m, mitochondrion; Av, apical vacuole; arrow, myelin figure; v, apical vesicles; Bm, basement membrane, G, Golgi complex.  $\times 11,300$ .







reported in the rat by MAUNSBACH [29] and SUZUKI [42], in several mammalian species by SJÖSTRAND [41] and in the rhesus monkey (*Macaca mulatta*) by TISHER, ROSEN and OSBORNE [45]. However, the material the present observations are based on was deemed inadequate to positively define this segmentation.

The initial or 'neck' region begins as an abrupt transition from the low-lying squamous epithelial cells lining Bowman's capsule to the tall columnar cells of the early proximal tubule (fig. 8). In tissue obtained by biopsy the lumen of this portion and the *pars convoluta* of the proximal tubule is usually occluded whereas in the living state the proximal tubule has been found to be patent [14, 15]. The tubular occlusion represents cellular debris and swollen disrupted cells. The cells of the *pars convoluta* of the proximal tubule are also columnar and possess a well developed brush border which is periodic acid-Schiff (PAS) positive (fig. 9). The cells are filled with mitochondria and various inclusion bodies. The cells of the *pars recta* are more cuboidal and the brush border is not as extensively developed (fig. 10). Cellular organelles are less numerous in this region of the proximal tubule. The transition from the terminal *pars recta* to the initial portion of the thin descending limb of Henle's loop was gradual (fig. 11) and characterized by large intracellular inclusions presumably representing lipofusion or 'degeneration' pigment. The gradual transition marked by pigment accumulation may be characteristic of this region in primates as a similar picture has been observed in the human kidney [43], and the rhesus monkey (*Macaca mulatta*) kidney [45].

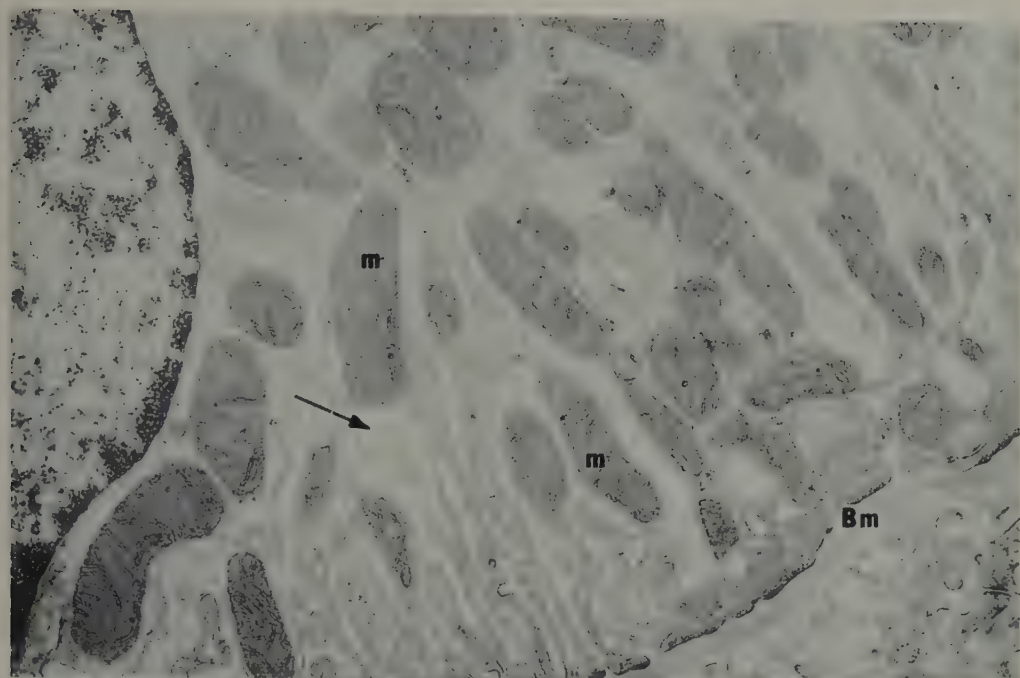
### B. Electron Microscopy

1. *Neck region and pars convoluta.* As noted by light microscopy, the transition from the low-lying squamous epithelium lining Bowman's capsule to the tall columnar cells of the initial or neck region of the proximal tubule is abrupt. The cells of the neck region and *pars convoluta* of the proximal tubule are virtually indistinguishable and will be described together. Much of this region

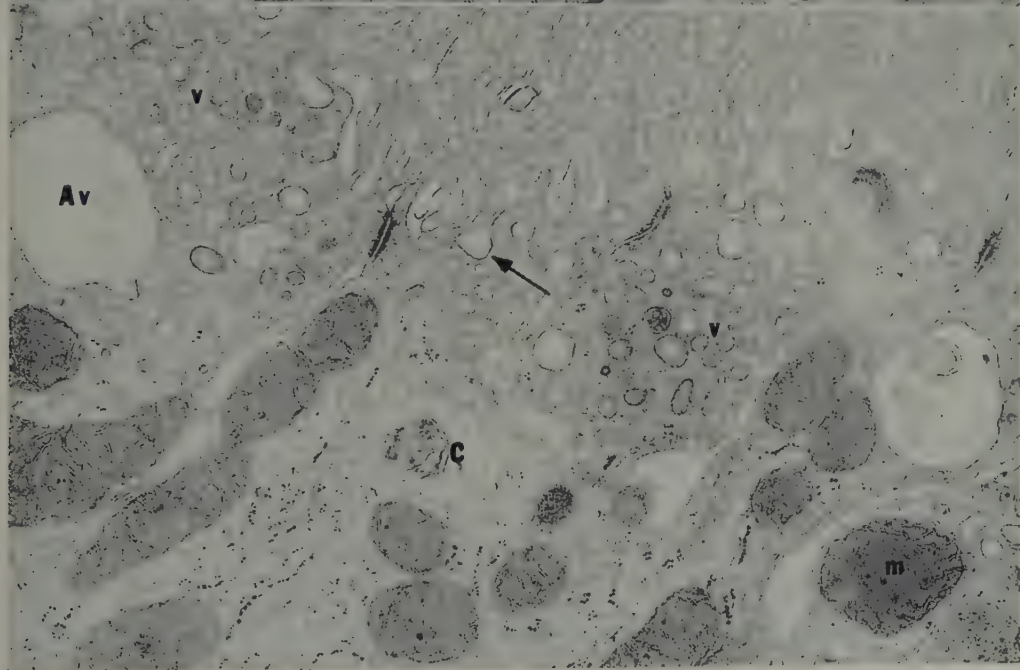
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*Fig. 13.* Electron micrograph showing the extensive invaginations of the basal plasmalemma enclosing elongate mitochondrial profiles (m) in the *pars convoluta* segment of the proximal tubule. Arrow, extracellular spaces; Bm, basement membrane.  $\times 14,700$ .

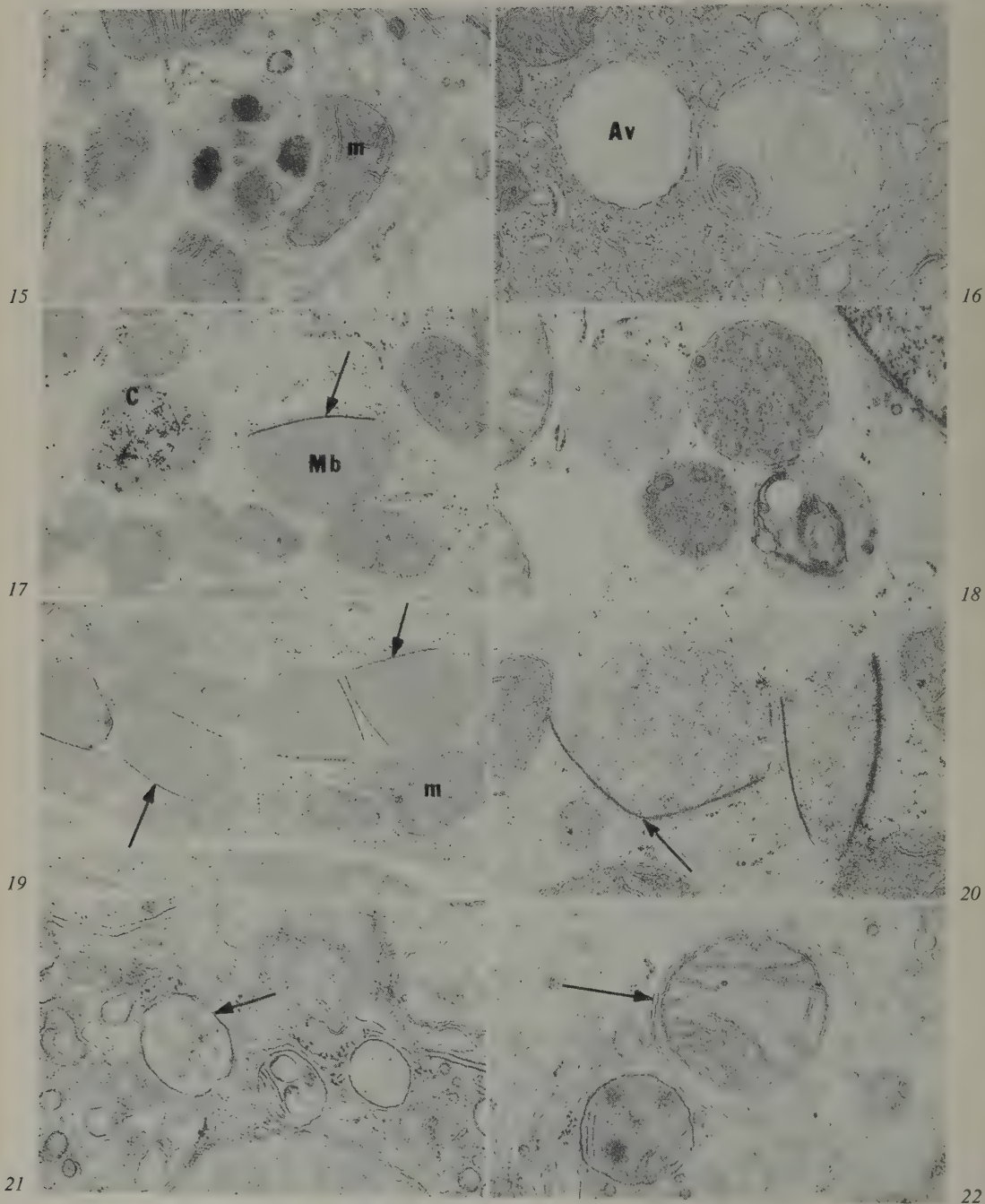
*Fig. 14.* Electron micrograph of the apical region of a proximal tubule cell characteristic of the *pars convoluta* segment. The apical plasmalemma forms invaginations (arrow) between individual microvilli. Av, apical vacuole; v, apical vesicles; C, cytosome; m, mitochondrion.  $\times 15,250$ .



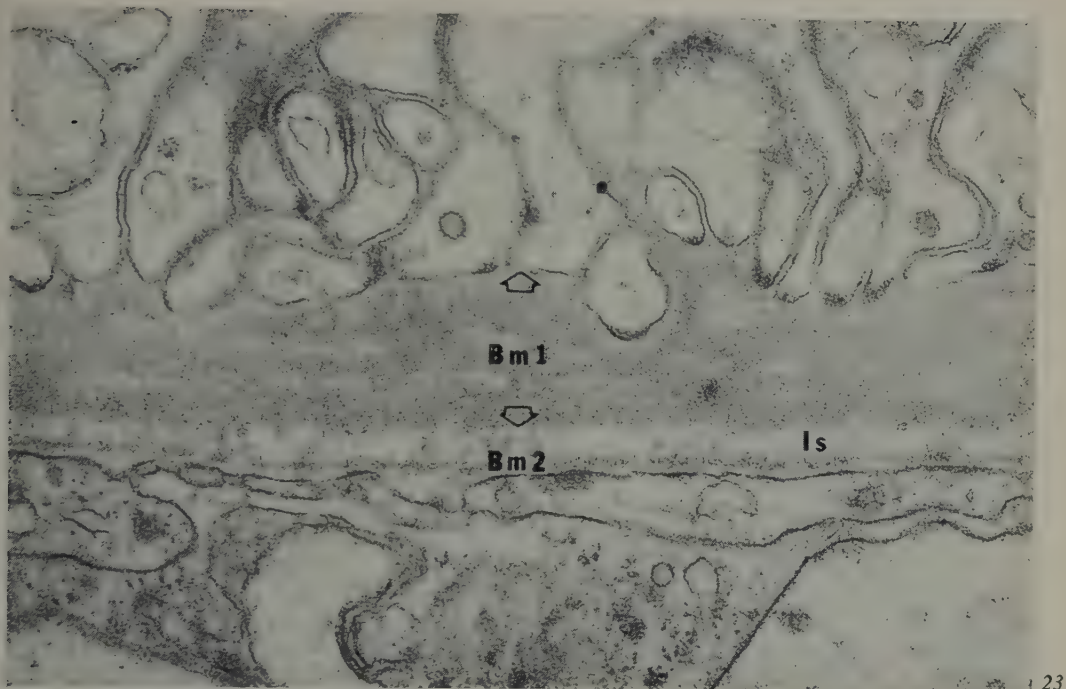
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*Fig. 15.* Electron micrograph of a cytosome containing multiple dense inclusions and membranous material. m, mitochondrion.  $\times 18,000$ .

*Fig. 16.* Electron micrograph of a cytosome filled with membranous whirls and an adjacent apical vacuole (Av).  $\times 14,125$ .

*Fig. 17.* Electron micrograph depicting a cytosome (C) containing minute electron dense inclusions and a nearby microbody (Mb) with a dense marginal plate (arrow).  $\times 17,500$ .

*Fig. 18.* Electron micrograph showing a cluster of four cytosomes of differing matrical density and varying matrical contents.  $\times 16,550$ .

*Fig. 19.* Electron micrograph depicting a group of microbodies of differing shapes. Each microbody exhibits a marginal plate (arrow) closely associated with profiles of endoplasmic reticulum. m, mitochondrion.  $\times 14,125$ .

*Fig. 20.* Electron micrograph of two microbodies which appear swollen as evidenced by a decrease in matrical density, an increase in volume, and bending of the marginal plates (arrow). See reference 45 for a complete discussion of the effects of tissue preparation on the appearance of microbodies.  $\times 17,300$ .

*Fig. 21.* Electron micrograph of a multivesicular body (arrow).  $\times 21,200$ .

*Fig. 22.* Electron micrograph of cytogresome (autophagic vacuole) containing a mitochondrion undergoing autolytic digestion (arrow).  $\times 21,200$ .

*Fig. 23.* Electron micrograph showing the basement membranes of two adjacent proximal tubules (Bm 1 and Bm 2). There is a marked difference in their thickness. Note that Bm 1 is multilayered. Is, interstitial space.  $\times 30,225$ .



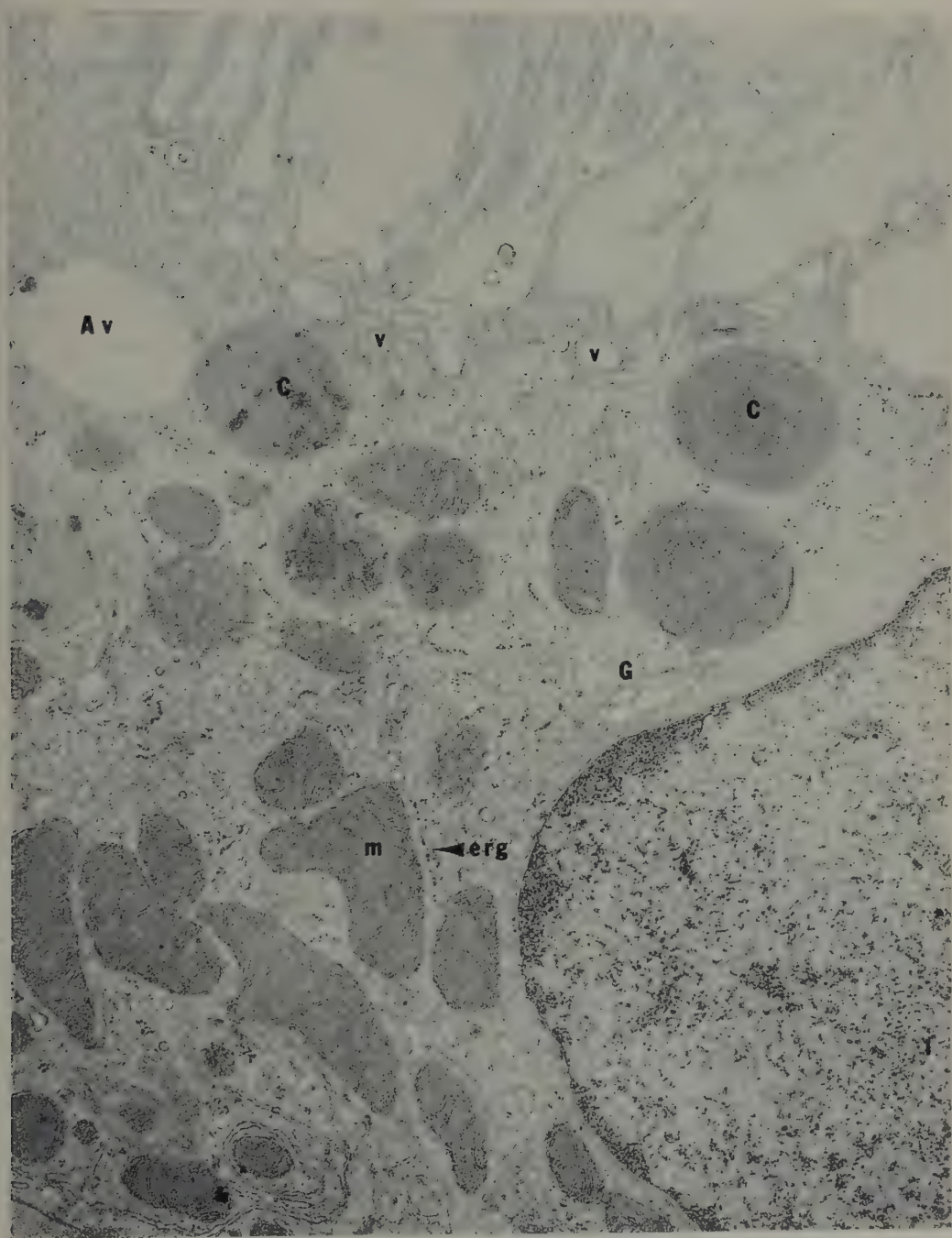
appears to correspond to the first segment of the proximal tubule as defined by MAUNSBACH [29] in the rat and discussed in an earlier section of this Chapter. The cells are tall and columnar in appearance (fig. 12). The cell membrane forms complicated invaginations often enclosing elongate mitochondrial profiles at the basal and lateral margins of the cell (fig. 12 and 13). Lateral interdigitations with adjacent cells are common and complex. At the luminal cell surface long slender microvilli compose the typical well-developed brush border. Between the microvilli deep invaginations are formed by the apical cell membrane. In the apical region of the cells within the *pars convoluta* there is a complex system of vesicles, larger vacuoles, and dense tubules (fig. 14). In some instances the vesicles merely represent cross-sections of the deeply invaginated apical plasmalemma.

The cells within this region contain four general morphologic types of single membrane-limited inclusion bodies (SMLIB) as defined by ERICSSON and TRUMP [10]. These include cytosomes, cytosegresomes (autophagic vacuoles), microbodies, and multivesicular bodies. Cytosomes and microbodies are the two most commonly observed types of inclusion bodies in the *pars convoluta*. Cytosomes vary considerably in size, content, and density (fig. 15–18). Microbodies also vary markedly in their appearance (fig. 19 and 20). In most instances they exhibit a relatively homogeneous background matrix and possess the typical marginal plate. Cytosegresomes (autophagic vacuoles) and multivesicular bodies are only infrequently present in this region of the nephron (fig. 21–22). Cell organization and the cellular components are comparable to most other epithelia. There are well-developed Golgi complexes lateral or just above the cell nucleus, basally-placed lipid droplets, abundant quantities of smooth and rough surfaced or granulated endoplasmic reticulum, free ribosomes, and microtubules scattered through the cytoplasm. The basement membrane is variable in thickness and often laminated in appearance (fig. 23).

2. *Pars recta*. The *pars recta* represents most of the straight descending portion of the proximal tubule. It is composed of simple cuboidal epithelium which often appears to have a slightly convex luminal surface covered by a less well-developed brush border (fig. 24). The apical vacuoles, vesicles, and

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Fig. 24. Electron micrograph of a typical proximal tubule cell from the *pars recta* segment. The brush border is not as well developed as in the *pars convoluta* and individual microvilli are spaced further apart. See text for additional description. m, mitochondrion; C, cytosome; Av, apical vacuole; v, apical vesicles; G, Golgi complex; erg, rough-surfaced endoplasmic reticulum.  $\times 17,280$ .



tubules are fewer in number in this region. Mitochondria are usually spherical, decreased in number, and much less likely to be enclosed by plications of the basal plasmalemma. The same single membrane limited inclusion bodies and other cellular organelles observed within the *pars convoluta* are present within this segment.

### C. Comparison with Human

In most respects the proximal tubule of the chimpanzee is nearly identical to that of the human. The initial transition region from the epithelium lining Bowman's capsule to the initial or 'neck' region is abrupt in both kidney types. The cells of the *pars convoluta* are similar in shape and size and in their subcellular complement of organelles. The same situation appears to prevail in the *pars recta*. In both man and the chimpanzee it is not yet possible to be entirely certain that there are actually three distinct segments of the proximal tubule as has been reported in certain mammals [42, 29, 41]. However, it is this writer's opinion based on extensive observations in the two primates that a similar segmentation does exist.

### D. Structural-Functional Correlation

The following comments regarding known functions of the proximal tubule are based on studies in various mammals and may not necessarily be similarly present in the chimpanzee. The proximal tubule is responsible for a variety of functions that can be classified into three major categories: electrolyte transport, transport of organic materials, and intracellular digestion. Up to 80% of filtered sodium can be reabsorbed by the proximal tubule, presumably by passive diffusion across the apical cell membrane and active extrusion via one or more sodium 'pumps' at the cell base. Such a 'pump' requires considerable energy. The cells of the *pars convoluta* appear especially adapted for sodium transport. On their luminal surface the elongate microvilli and deep invaginations of the apical plasmalemma provide a vast cell surface for sodium and water diffusion into the cells. The intricate invaginations of the basal plasmalemma closely associated with numerous mitochondria appear to satisfy the requirement for energy near the site of the sodium 'pump' which presumably is at the cell base. In addition, adenosine triphosphatase (ATPase) activity has been demonstrated in association with the plasmalemma [33].

In the *pars convoluta* the organization of the cell apex is also well suited for

absorption of substances such as protein [5, 6, 7], other colloidal particles [47], vital dyes [47], and mannitol, sucrose, and glucose [30, 50] from the glomerular filtrate. These substances have been shown to enter the cell via endocytosis and undergo breakdown and digestion due at least in part to the numerous hydrolytic enzymes located in the lysosomes. In addition, through the process of autophagocytosis, small amounts of cellular cytoplasm are segregated and similarly digested. By the process of exocytosis non-digestible material leaves the cell at the luminal border.

At least two separate active secretory mechanisms exist in the proximal tubule for the handling of organic material. Both require energy production which is presumably supplied by mitochondrial ATP synthesis. One mechanism transports organic acids such as penicillin, phenol red, chlorphenol red, para-amino hippurate, diodrast, and creatinine. A second transport system handles organic bases including N-methyl-nicotinamide, guanidine, and histamine [37].

## V. THIN LIMB OF HENLE'S LOOP

### *A. Light Microscopy*

The thin limb of Henle's loop begins at the transition from the terminal proximal tubule or *pars recta* (fig. 11). This transition region divides the outer medulla into the inner and outer stripes [36]. The thin loop extends downward into the inner medulla and then turns back on itself to form hairpin loops. The transition from the thin to the thick segment may occur on either the descending or ascending portions of the loop. This transition region marks the boundary between the inner medulla and the inner stripe of the outer medulla [36]. The thin limbs are lined by low-lying squamous epithelium which is usually attenuated except in the region of the nucleus which bulges out into the tubular lumen (fig. 25-26). The basement membrane of the thin limbs is generally much greater in thickness than that of most other tubular segments of the nephron and is PAS-positive. Subcellular organelles are generally sparse within these cells.

### *B. Electron Microscopy*

Two morphologic patterns of tubular structure are noted by electron microscopy in the thin limbs of the loop of Henle. This difference is based solely on the appearance of the lateral interdigitations of adjacent cells. One pattern



consists of highly complex interlocking interdigitations between adjacent cells which extend from the luminal to the basement membrane surfaces (fig. 27). The second morphological pattern lacks the complex interdigitating processes (fig. 28). In all other respects the two types of thin limb cells appear similar (fig. 29). Mitochondria are small often tortuous, and sparse. The other typical subcellular organelles including cytosomes, multivesicular bodies, autophagic vacuoles, and endoplasmic reticulum are also sparse within these cells. The cytoplasm consists of a thin flocculent material which contains small numbers of free ribosomes and occasional thin filaments coursing randomly through the cell. The typical Golgi complex is present but not extensive. The appearance of the basement membrane represents one of the most distinctive features of the thin limbs. It is very thick and almost always multilayered. Immediately beneath the cells the layers become more irregular, distorted and separated (fig. 27, 28, 29). Frequently, small projections of basement membrane material extend upward between interdigitating processes of adjacent cells or into irregular invaginations along the basal surface of the cell.

Although it is tempting to speculate on the possible significance of the two different morphologic patterns of thin limb cells noted in the chimpanzee, the present observations do not clearly define whether the two patterns represent ascending and descending thin limb segments or simply differences in cell configuration along the extent of either limb. In rats, however, it has been shown that the early part of the descending thin limb is more complex in shape [34].

### *C. Comparison with Human*

In virtually all respects the thin limb of the chimpanzee resembles that of the human. The general cell shape and configuration as well as the makeup of

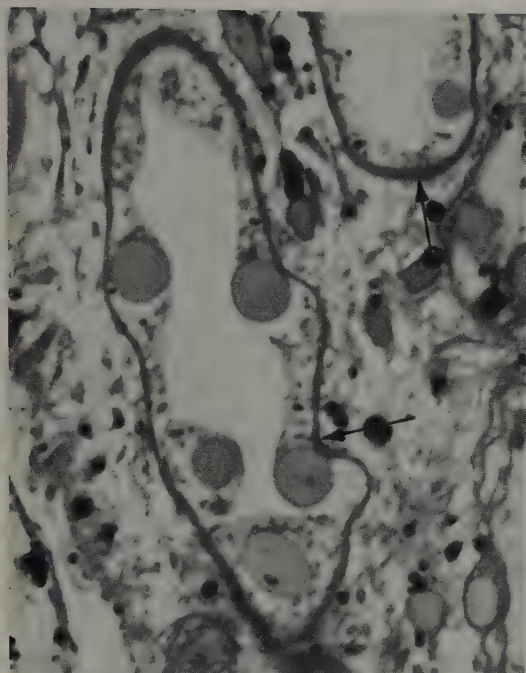
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*Fig. 25.* Photomicrograph depicting portions of two typical thin limb segments. The cells are squamous, greatly attenuated except in the region of the nucleus, and contain few cellular organelles. Note that the basement membranes (arrow) are thick and very prominent.  $\times 1000$ .

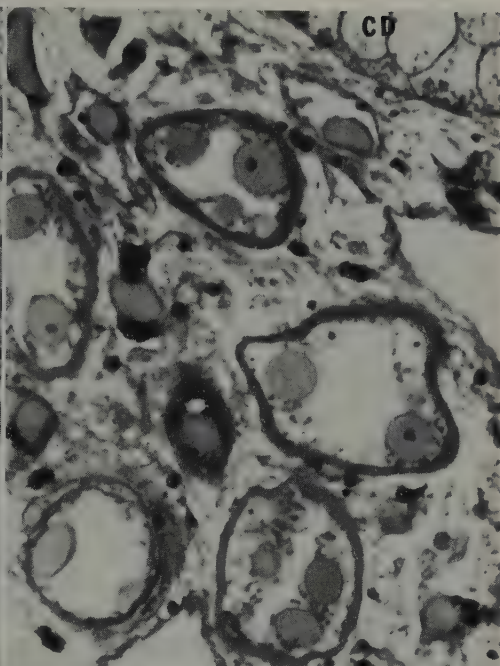
*Fig. 26.* Photomicrograph showing cross sections of typical thin limbs of Henle's loop. Compare the relative thickness of their basement membrane with the basement membrane of the collecting duct (CD).  $\times 830$ .

*Fig. 27.* Electron micrograph showing a short segment of a thin limb. The lateral interdigitations of adjacent cells are highly complex. Compare with figure 28. The basement membrane (Bm) is very thick and multilayered.  $\times 9,050$ .

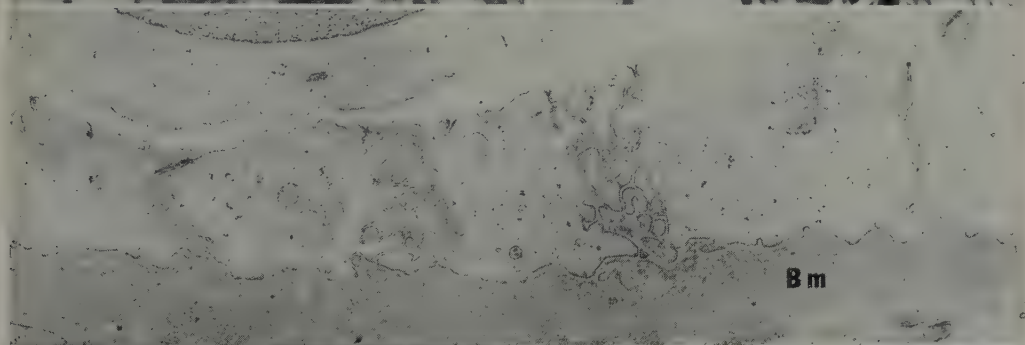
*Fig. 28.* Electron micrograph of a short segment of a thin limb. Note the lack of extensive lateral cellular interdigitations. See text for discussion.  $\times 11,300$ .



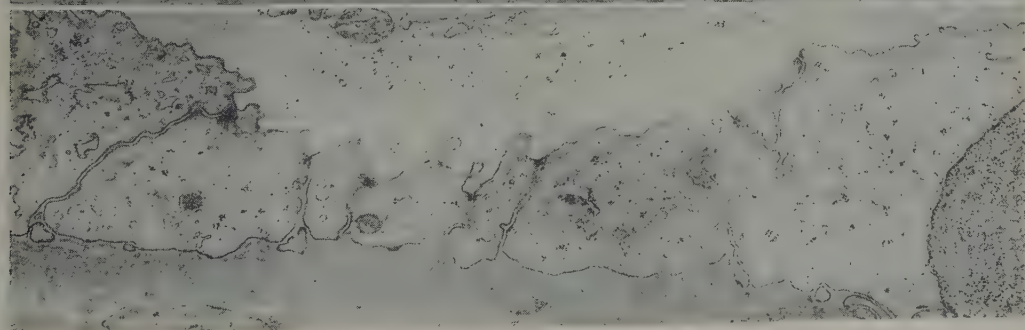
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subcellular organelles is similar. In both primates, the basement membrane is very thick and multilayered.

#### *D. Structural-Functional Correlation*

The loop of Henle is important in the process of urinary concentration. As proposed in the countercurrent hypothesis [24], the loop of Henle acts as a countercurrent multiplier to establish a longitudinal concentration gradient which increases progressively from the cortex to the papillary tip [40]. The ascending thin limb must transport sodium from the tubular lumen to the interstitium to help establish this concentration gradient for sodium. Micro-puncture studies in the rat by JAMISON, BENNETT and BERLINER [19] and JAMISON [18] have shown such a finding. However, cells highly specialized for ion transport (such as are present in the ascending thick segment of the loop of Henle – see next section of this chapter), generally appear more complex in structure than those lining the ascending thin limb of the chimpanzee as well as other mammals. As a result there remains an unresolved discrepancy in the structural-functional correlation for this segment of the nephron.

A second unresolved problem of structural-functional correlation in this segment concerns the characteristics of the two thin limbs in their handling of water. For the countercurrent hypothesis to be correct it is necessary for the thin descending limb to be permeable to water, while the ascending limb must be impermeable to water. Thus far, no morphologic explanation for this physiologic difference has been convincingly shown.

### VI. DISTAL TUBULE

#### *A. Light Microscopy*

The distal tubule is composed of three distinct segments which include the *pars recta* or ascending thick limb of Henle, the *macula densa* adjacent to the 'parent' renal corpuscle, and the *pars convoluta*. The distal tubule begins as

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*Fig. 29.* Electron micrograph showing the typical appearance of cells of the thin limb of Henle's loop. Organelles are sparse. The basement membrane (Bm) is thick and multilayered. L, lumen of tubule; m, mitochondrion; erg, rough-surfaced endoplasmic reticulum; G, Golgi complex; f, filaments.  $\times 12,700$ .





the *pars recta* at the transition from the thin ascending limb of Henle (fig. 30). This transition region marks the junction between the inner medullary zone and the inner stripe of the outer medullary zone [36]. The tubular lumen throughout the distal tubule is patent. The *pars recta* and *pars convoluta* are similar in appearance being cuboidal in shape. These cells typically exhibit numerous mitochondria which nearly fill the cells. The *macula densa* is that

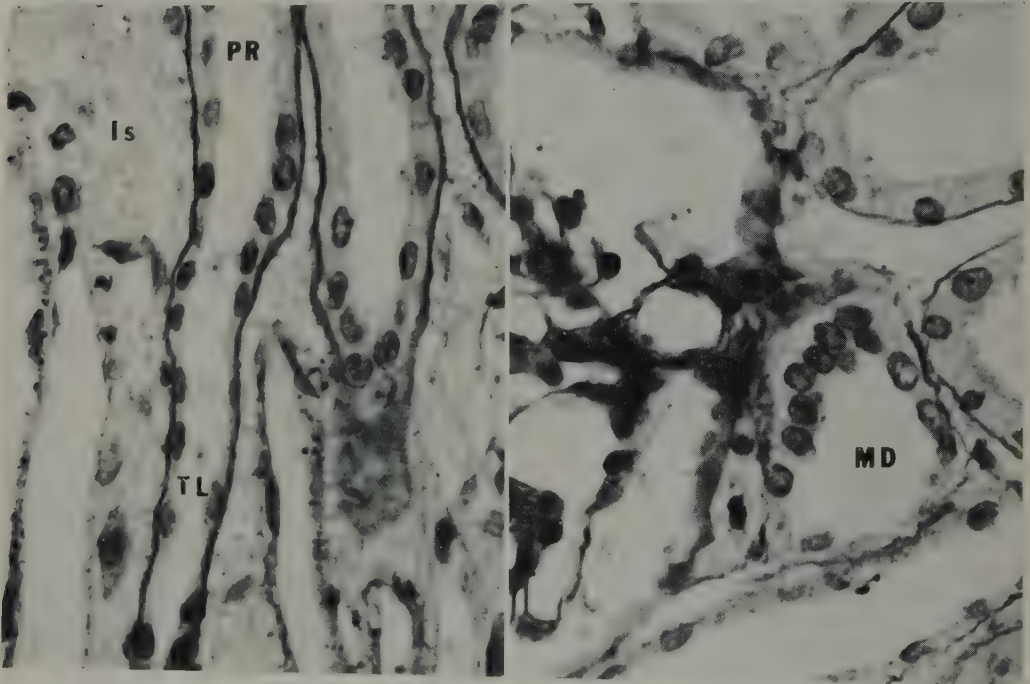
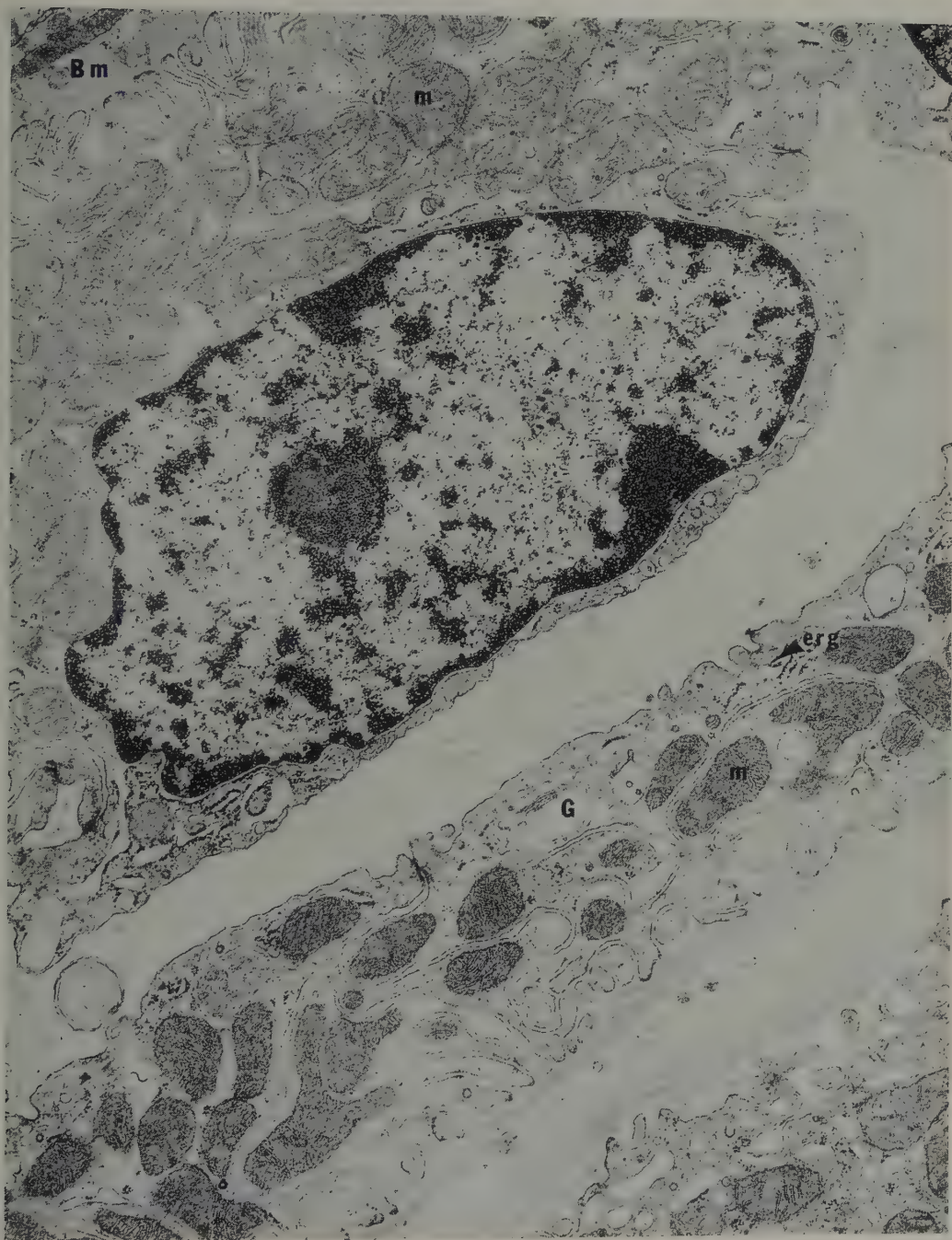


Fig. 30. Photomicrograph depicting the transition from the lowlying squamous epithelium of the thin limb of Henle's loop (TL) below to the cuboidal epithelium of the early thick segment of Henle's loop or *pars recta* (PR) of the distal tubule above. Is, interstitial space.  $\times 650$ .

Fig. 31. Photomicrograph showing a portion of a renal corpuscle and its contiguous *macula densa* (MD), the specialized segment of the distal tubule adjacent to the hilus. Note that the *macula densa* cells on the glomerular side of the tubule are tall and exhibit apically-placed nuclei.  $\times 630$ .

Fig. 32. Electron micrograph of the *pars recta* segment of the distal tubule. The cells are packed with mitochondria (m) that are enclosed by extensive plications of the basal plasmalemma. Bm, basement membrane; erg, rough-surfaced endoplasmic reticulum; G, Golgi complex.  $\times 13,000$ .



specialized portion of the distal tubule that comes into contact with the glomerulus at the pole and is composed of columnar cells with apically-placed nuclei (fig. 31).

### *B. Electron Microscopy*

1. *Pars recta*. The *pars recta* is composed of cuboidal epithelium containing numerous elongate mitochondria enclosed by plications or invaginations of the basal plasmalemma (fig. 32). These invaginations sometimes extend to a distance of two-thirds or more into the cell toward the luminal border. Other subcellular organelles within this segment of the nephron include a well-developed Golgi complex abundant quantities of smooth and rough-surfaced endoplasmic reticulum, multivesicular bodies, and cytosomes. Numerous small vesicles are often present along the luminal surface of the cells. Microbodies are not present within the distal tubule.

2. *Pars convoluta*. Although the cells of the *pars convoluta* are usually low columnar in appearance, they are otherwise nearly identical in morphology to the cells of the *pars recta* (fig. 33). Again, the cells are nearly filled with mitochondria enclosed within plications of the basal plasmalemma. The complement of other subcellular organelles is identical to that of the *pars recta*.

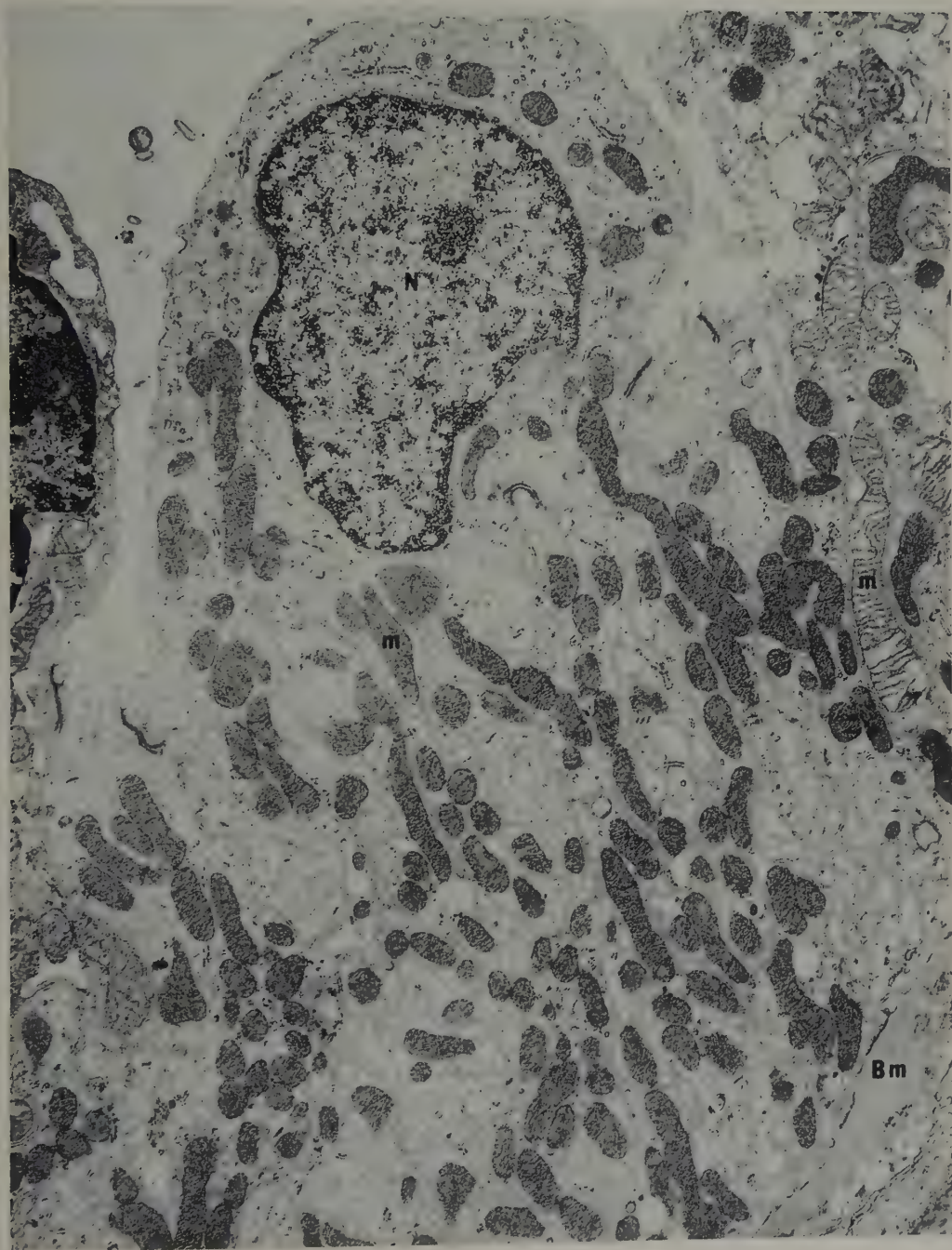
### *C. Comparison with Human*

The distal tubule of the chimpanzee is nearly identical in appearance to that of the human kidney. Observations in the region of the *macula densa* were too limited to entirely exclude more subtle differences, however, no marked variation between man and chimpanzee was noted. Although dark or intercalated cells have been observed in the distal tubule of the rat [16] and human kidney [44] (the latter probably in the transition region between the distal tubule and the collecting duct), a similar finding was not noted in the chimpanzee. However, this may simply relate again to the limited number of observations in this region rather than to any significant morphologic variation.

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Fig. 33. Electron micrograph showing typical cells of the *pars convoluta* segment of the distal tubule. The main difference between this segment and the *pars recta* is the slightly greater cell height in the former. The subcellular components are similar both qualitatively and quantitatively. Bm, basement membrane; m, mitochondrion; N, nucleus.  $\times 10,375$ .







### D. Structural-Functional Correlation

Very little is known about the structural-functional relationships of the distal tubule as a whole. This is particularly true of the *pars convoluta*. However, in the countercurrent hypothesis of urine concentration [24] the ascending limb of Henle must be capable of sodium ion transport from the tubular lumen to the interstitium. The thick segment of the ascending limb of Henle or *pars recta* of the distal tubule is capable of such a function. In the rhesus monkey, an animal without long ascending thin limbs of Henle, but with ascending thick limbs (*pars recta*) [46], micropuncture data [2] revealed the presence of a hypotonic filtrate entering the distal convoluted tubule (*pars convoluta*). This is thought to imply the presence of an active sodium transport mechanism in this segment of the distal tubule.

## VII. COLLECTING DUCT

### A. Light Microscopy

The collecting duct can be divided into four distinct regions which include the cortical segment, the medullary ray segment, the outer medullary segment and the inner medullary or papillary segment. In the chimpanzee kidney there is a gradual transition from the characteristic distal tubule cell with its complex internal structure of elongate mitochondria and other cellular organelles to the more simple appearing collecting duct cells. There are two basic cell types within the collecting duct, the light or pale cells which are more numerous and the 'dark' or intercalated cells. The latter cell type is present in greatest

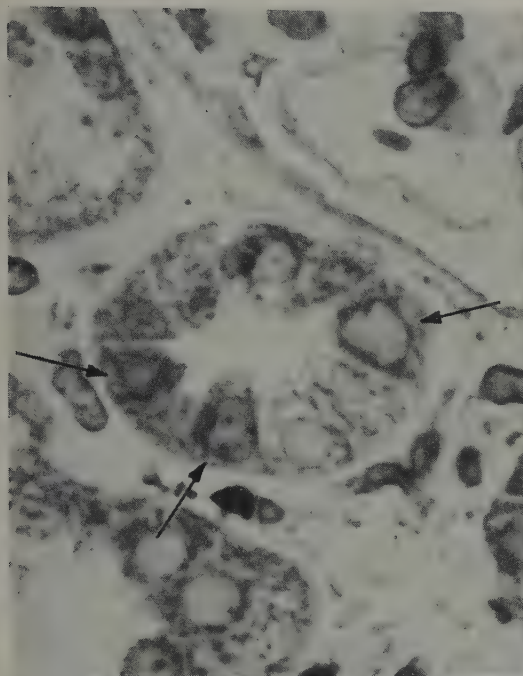
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Fig. 34. Photomicrograph of cortical collecting duct. Note the dark or intercalated cells (arrows) intermingled with the light cells.  $\times 1,100$ .

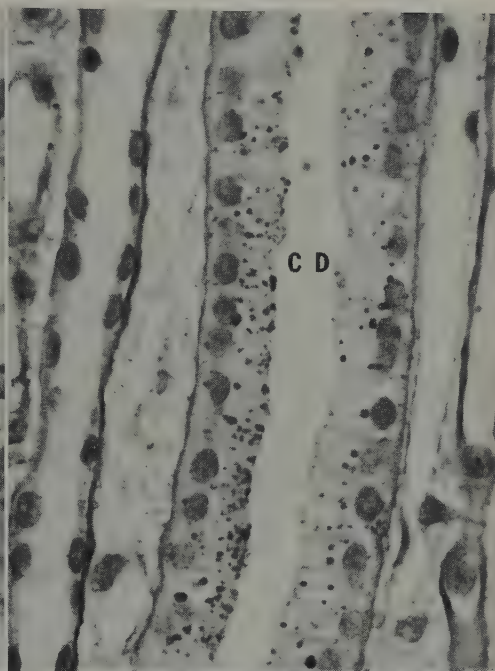
Fig. 35. Photomicrograph of the collecting duct (CD) as it typically appears in the outer medulla. The cells are columnar and often contain numerous PAS positive granules in their cytoplasm.  $\times 560$ .

Fig. 36. Photomicrograph showing a cross-section of a typical duct of Bellini or papillary duct near the papillary tip. The epithelium is transitional in character but still contains cells resembling dark or intercalated cells (arrow).  $\times 430$ .

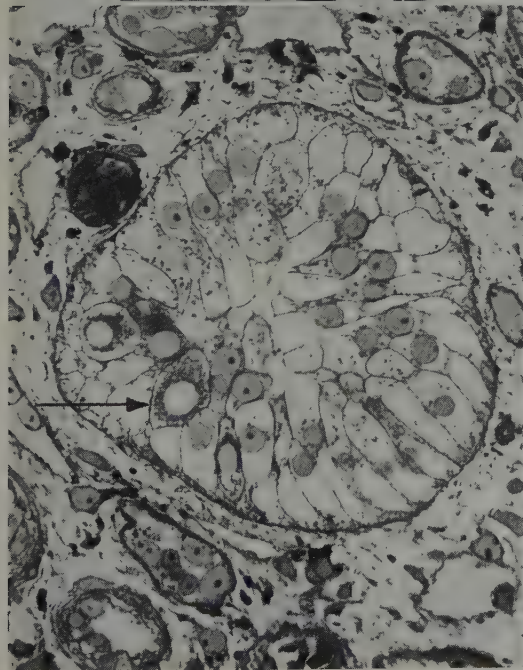
Fig. 37. Photomicrograph of a duct of Bellini cut on longitudinal section, on the left, (CD) and a thin limb of the loop of Henle, to the right (TL). The epithelium of the duct of Bellini is becoming transitional in character at this level. Note that the basement membrane of the thin limb is much thicker than that of the collecting duct.  $\times 700$ .



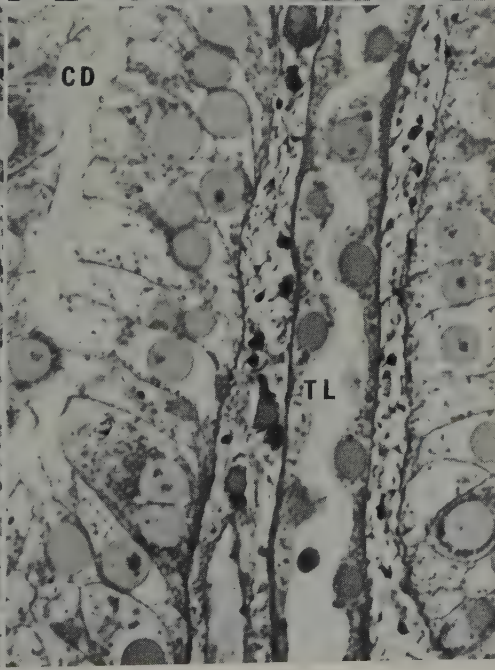
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number in the cortical collecting segment and decreases steadily in frequency as the collecting duct descends toward the papillary tip. The typical light cells contain relatively few organelles while the dark cells are filled with mitochondria and various inclusion bodies and display a more dense staining cytoplasm. Cells of the cortical collecting duct are cuboidal to low columnar in shape (fig. 34). The cells of the medullary ray segment gradually increase in height and are columnar as the collecting duct passes into the outer medullary segment (fig. 35). In the inner medullary segment the collecting ducts are lined by tall columnar epithelium. At the extreme papillary tip collecting ducts join to form the ducts of Bellini or papillary ducts which are lined by transitional epithelium (fig. 36–37). This epithelium is continuous with the transitional epithelium overlying the papillary tip in the area cribosa. The concentration of organelles within individual light cells decreases progressively as the collecting duct descends toward the papillary tip.

There appear to be two or three separate subdivisions or branchings of the collecting duct when viewed or traced from the papillary tip upward toward the cortex. The first occurs approximately at the level of the collecting duct where the lining epithelium changes from transitional to columnar. One and sometimes two subdivisions or branchings occur before the collecting duct reaches the outer medulla. Rarely the collecting duct is seen to branch in the outer medulla.

In comparison with the thin limb of Henle's loop, the basement membrane of the collecting duct is much thinner and less distinct (fig. 36, 37).

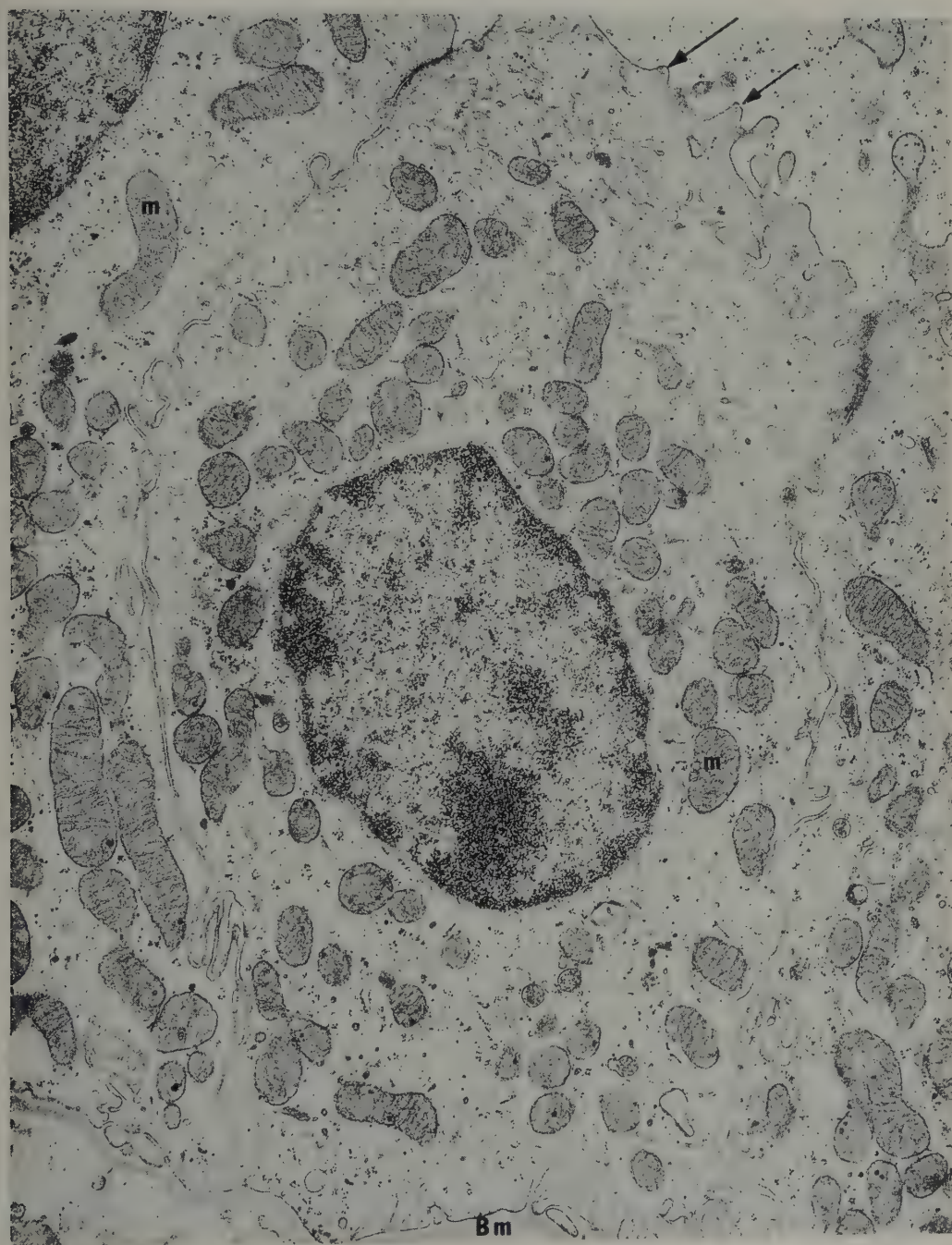
### *B. Electron Microscopy*

*1. Light cells.* The light or pale cells are the principle cells of the collecting duct. In the cortical segment the cells are cuboidal to low columnar (fig. 38). The apical plasmalemma forms small blunt microvilli covered with a thin layer of glycocalyx or 'fuzz'. Lateral interdigitations with adjacent cells are limited in extent and are in the form of small short interlocking processes. True basilar infolding are observed but plications of the basal plasmalemma are not extensive in the collecting duct. The nucleus assumes a mid to basal

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*Fig. 38.* Electron micrograph of a typical light cell in the cortical collecting duct. Lateral interdigitations with adjacent cells are largely confined to short interlocking processes. Short blunt microvilli (arrows) are evident on the apical cell surface. m, mitochondrion; Bm, basement membrane;  $\times 15,120$ .







position. The Golgi complex typically lies lateral and just above the nucleus (fig. 38). In comparison with the proximal and distal tubules, the number of mitochondrial profiles is markedly reduced in the cells of the collecting duct. In addition, they are more often spherical or ovoid and not enclosed within plications of the basal plasmalemma.

Inclusion bodies within this region include cytosomes, multivesicular bodies, and cytosegresomes (autophagic vacuole). The multivesicular bodies are common in these cells and they are often very large and irregular in shape. Microbodies are not present in the collecting duct.

The cell cytoplasm contains randomly scattered profiles of smooth and rough-surfaced endoplasmic reticulum, clusters of free ribosomes, occasional lipid droplets, and small vesicles near the apical surface.

The junctional complex includes the tight and intermediate junctions near the lumen and occasional desmosomes deeper in the cell toward the basal surface.

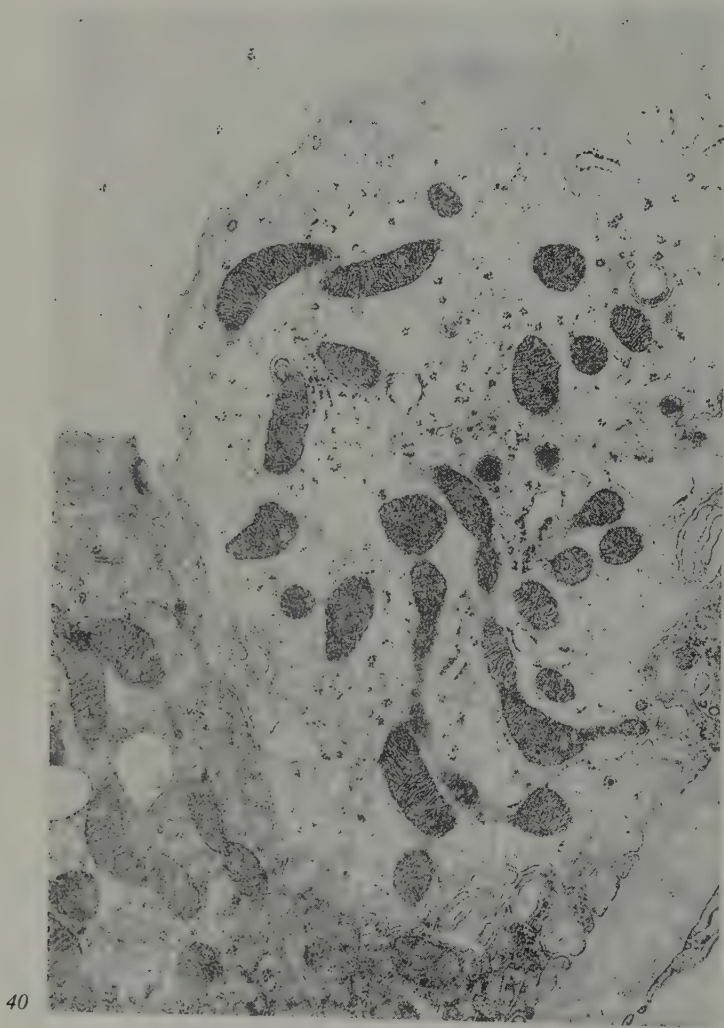
As the collecting duct descends into the medulla, the typical cells of the collecting duct increase in height, but the concentration of their cellular organelles decreases significantly. Near the papillary tip the collecting ducts merge to form the ducts of Bellini which are lined by transitional epithelium. The basement membrane is relatively thin and uniform in appearance in the cortex but increases slightly in thickness and occasionally becomes multilayered in the inner medulla.

*2. Dark cells.* The 'dark' or intercalated cell differs from the light cell in several respects (fig. 39). These cells are often rounded in shape. They usually exhibit more complex plications of their basal plasmalemma and possess greater numbers of short blunt microvilli on their apical surface. They contain more mitochondria, cytosomes, and multivesicular bodies and small vesicles near the luminal surface are often more numerous. The cytoplasm is more dense (fig. 39-40), and often contains increased numbers of free ribosomes and increased amounts of rough-surfaced endoplasmic reticulum.

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*Fig. 39.* Electron micrograph depicting a dark or intercalated cell within the cortical segment of the collecting duct. Note that in comparison with the light cell (fig. 38) the dark cell exhibits more apical microvilli, a denser cytoplasm, complex plications of the basal plasmalemma, increased quantities of free ribosomes, and a greater concentration of subcellular organelles. Ptc, peritubular capillary.  $\times 15,820$ .





*Fig. 40.* Electron micrograph showing the marked difference in cytoplasmic density between a dark cell, left, and a light cell, right, both within the cortical segment of the collecting duct.  $\times 13,000$ .

*Fig. 41.* Electron micrograph demonstrating the appearance of interstitial cells characteristic of the inner medulla. The cells are irregular in shape and contain lipid droplets (Li), abundant quantities of rough-surfaced endoplasmic reticulum (erg), and small vesicles. G, Golgi complex.  $\times 11,500$ .







### *C. Comparison with Human*

The collecting duct of the chimpanzee kidney is nearly identical in appearance to that of the human kidney. The major difference is in the papillary region where the ducts of Bellini are lined with transitional epithelium in the chimpanzee but not in the human. Transitional epithelium also covers the papillary tip in the area cribosa in the chimpanzee while the same region in the human kidney is covered by tall columnar cells.

### *D. Structural-Functional Correlation*

Although many functions have been ascribed to the distal nephron including potassium secretion, urine acidification, and ammonia production [38], no precise separation has been made between those functions that are performed by the *pars convoluta* of the distal tubule and those that are the responsibility of the collecting duct. In addition, absolutely no knowledge of which subcellular organelles are involved in these various functions is currently available. However, GANOTE, GRANTHAM, MOSES, BURG and ORLOFF [13] have recently observed that isolated collecting duct segments of the rabbit exhibit dilatation of lateral extracellular spaces, bulging of apical cell membranes into the tubular lumen, and formation of intracellular vacuoles during vasopressin-induced periods of high osmotic water transport. Vasopressin alone induced no detectable direct morphologic effects on subcellular organelles and the above described changes were interpreted as being the result of transepithelial bulk water flow.

## VIII. INTERSTITIUM

The interstitium, although present throughout the kidney, is best developed in the medulla. In the regions of the papillary tip interstitial cells are very abundant. The typical interstitial cell is extremely irregular in shape and extends processes which lie in close proximity to the renal tubules and vessels (fig. 41). The cells are rich in lipid droplets, rough surfaced endoplasmic reticulum, and mitochondria and, in addition, contain the usual organelles. Within the interstitial space clumps of basement membrane material and fibers of varying diameter, many of which resemble collagen, are present.

Very little is known regarding the function of the interstitial cells. See TRUMP and BULGER [49] for a recent review concerning the possible role of these cells in the kidney.

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## EXPLANATION OF ABBREVIATIONS

Av	Apical vacuole	MD	macula densa
Bm	basement membrane	Me	mesangial cell
Bc	Bowman's capsule	Mm	mesangial matrix material
Bs	Bowman's space	Mb	microbody
Bb	Brush border	m	mitochondrion
CL	Capillary lumen	N	nucleus
CD	Collecting duct	Pc	parietal epithelial cell
C	cytosome	PR	pars recta
En	endothelial cell	Ptc	peritubular capillary
f	filaments	p	process (mesangial cell)
fp	foot processes	erg	rough-surfaced endoplasmic reticulum
G	Golgi complex	TL	thin limb of Henle
Is	interstitial space	v	vesicles
Li	lipid droplet	Vc	visceral epithelial cell
L	lumen of tubule		

Note: Figures 8, 10, 11, 30, 31 and 35 represent tissue fixed by intravascular perfusion with 10% neutral buffered formalin, embedded in paraplast, and stained by the periodic acid-Schiff method.

Figures 1, 9, 25, 26, 34, 36, 37 represent tissue obtained by percutaneous renal biopsy and fixed in osmium tetroxide or 6.25% glutaraldehyde and embedded in epon resin [28]. Sections of 0.5–1.0  $\mu$  thickness were stained with toluidine blue [51].

Figures 2–7, 12–24, 27–29, 32, 33, 38–41 represent the same biopsy tissue described above, but prepared for electron microscopy by thin sectioning and double staining with uranyl acetate for 30–120 min and lead hydroxide (Millonigs) for 5–10 min. All specimens were viewed in an RCA-EMU 3H electron microscope.

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Author's address: Dr. C. CRAIG TISHER, Department of Medicine, Duke University Medical Center, Durham, NC 27706 (USA).

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## RENAL FUNCTION IN THE CHIMPANZEE

J. A. GAGNON

Division of Medicine, Walter Reed Army Institute of Research, Washington, DC

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### INTRODUCTION

Over the past several decades great progress has been made in uncovering many of the secrets of the kidney in man. Much of this information has been extrapolated from studies performed on a variety of animals utilizing such techniques as micropuncture, stop-flow, electron microscopy, isotope labeling, etc. Despite the aid of such sophisticated techniques there continues to

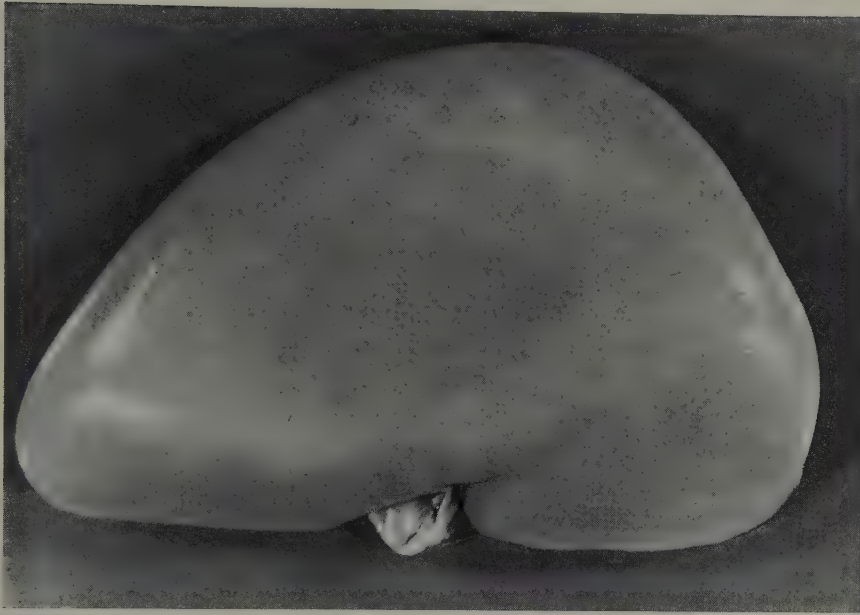
exist needs which have not been realized. One such need is for a greater understanding of how the kidney functions when subjected to the stresses of a strange and hostile environment. In the exploration of outer space man has sought the aid of an animal, more closely related to himself, to help answer some of the unknowns. Such an animal would have to be one which is socially and psychologically similar to man and whose manual dexterity allows him to perform semi-skilled tasks. The many similarities between the chimpanzee and man make this animal a desirable experimental subject. One obstacle presently confronting investigators in the use of this animal is the relative lack of biological information. Limited use of this primate in biological research stems from the problems of care, handling and accessibility, all of which add up to inadequate finances. Since this appears to be less of a factor today greater use of the chimpanzee is being made and much more is planned. The relative success of this sub-human primate as a kidney donor for human use also adds to the attractiveness of this animal.

The objective in compiling the following information pertaining to the renal physiology of the chimpanzee has been not merely to provide a source of reference but more importantly to emphasize the amount of work which still needs to be completed in this area before renal functions in the normal and stressful state can be extrapolated to man.

*Anatomy.* The kidneys of the chimpanzee (*Pan*) are paired organs situated in the posterior part of the abdomen on each side of the vertebral column and posterior to the peritoneum. Their shape generally resembles those of man, having a characteristic form similar to a bean. They tend, on occasion, to appear rather triangular in frontal section (fig. 1). The caudal pole is usually the tapered one.

The right kidney has been found most often to be more caudal than the left [1, 2, 3] but the left may actually be found lower [3]. LABINOWA [2] observed that the vertical extent of the right kidney corresponded to the first four lumbar vertebrae while the left kidney extended from the twelfth thoracic vertebra to the third lumbar. The position of the kidney, however, does not appear to influence the height of origin of the renal arteries since both arteries arise at approximately the same level in *Pan* [4]. In man, the right kidney is also more caudal than the left, lying 8–12 mm lower in most cases; its vertical extent corresponds to the last thoracic and upper two or three lumbar vertebrae [5].

SONNTAG [1] found the relative positions of the structures in the hilum to be as in man. He also observed, in a young, female chimpanzee that the left renal artery gives off suprarenal arteries, branches to the renal capsule, two



*Fig. 1.* Photomicrograph of the surface of the left kidney of an immature female chimpanzee (*Pan*) depicting the triangular shape of the organ. Courtesy of Dr. C. CRAIG TISHER.

small branches which anastomose with the lumbar arteries and an artery to the left ovary. The right renal artery likewise, gives off suprarenal and capsular vessels but none to the right ovary. As in man, the right ovarian artery branches directly from the aorta. The left ovarian and suprarenal veins drain into the left renal vein while the right vessels drain into the vena cava. The left spermatic vein has also been found to drain into the left renal vein [6].

The length of the kidneys of a young, female [1] was found to measure: right 6.6 cm, left 5.5 cm; breadth: right 3.3 cm, left 3.3 cm; thickness: right 1.8 cm, left 1.6 cm.<sup>1</sup>

KENNARD and WILLNER [7] have reported the weights of the two kidneys to be variable. Of the twenty-seven chimpanzees in which weights of both kidneys are given (table I), the left was heavier in thirteen instances, the right in ten, and in four instances the weights were equal. The mean weight of all

1 The measurements of the right kidney (67.1 g) of a healthy 23.9 kg female were: length 7.5 cm, breadth 4.2 cm, thickness 2.5 cm, cortex 1.3 cm, outer medulla 0.7 cm and inner medulla 1.2 cm.



the left kidneys in this group of 27 immature animals was 45.4 g and the right, 43.9 g.

The kidney of the infant chimpanzee is relatively large (table I). The ratio of combined weight of both kidneys to total body weight is 1:120 (group 1). As the animal approaches the age of puberty (group 4) the ratio has already increased to 1:167 (table I). Whether this relative decrease in kidney weight continues until the animal reaches maturity can only be speculated upon because of the lack of data on mature chimpanzees.

Table I. Kidney weights of thirty-one chimpanzees

Animal Sex	Investi- gator	Body weight kg	Weight both kidneys g	Body weight Kidney weight	Weight of kidneys Right g	Left g
Group 1 (infants)						
F	STRAUS <sup>1</sup>		26.0			
M	KENNARD <sup>2</sup>	2.90	18.06	161	8.94	9.12
F	KENNARD	3.65	37.79	96	18.55	19.24
Mean		3.27	27.28	120	13.74	14.18
Group 2 (5-10 kg Body weight)						
M	KENNARD	5.65	72	78	38.00	34.00
F	KENNARD	6.20	91	68	43.00	48.00
F	KENNARD	7.70	42	183	21.00	21.00
F	KENNARD	9.50	105	90	50.00	55.00
Mean		7.26	77.5	94	38.00	39.5
Group 3 (10-20 kg Body weight)						
F	KENNARD	10.40	70	149	35.00	35.00
F	KENNARD	11.20	66	170	31.33	34.70
F	KENNARD	11.70	98	119	50.00	48.00
F	KENNARD	11.90	60	198	30.00	30.00
F	KENNARD	12.50	97	129	45.00	52.00
M	KENNARD	13.85	82	169	40.33	42.19
M	KENNARD	14.20	82	173	41.00	41.00
M	KENNARD	14.50	99	146	50.33	48.84
F	KENNARD	15.20	134	113	66.00	68.00
F	KENNARD	15.25	56	272	32.00	24.00
F	KENNARD	16.45	137	120	65.00	72.00
M	KENNARD	17.30	103	168	51.84	51.32

Table I. (Continued)

Animal Sex	Investi- gator	Body weight kg	Weight both kidneys g	Body weight Kidney weight	Weight of kidneys Right g	Left g
Mean		13.71	90.3	152	44.8	45.6
Group 4 (over 20 kg Body weight)						
F	KENNARD	20.40	121	169	61.00	60.00
M	KENNARD	21.55	151	143	68.00	83.00
F	KENNARD	23.00	158	146	75.00	83.00
F	KENNARD	23.40	104	225	60.60	43.62
M	KENNARD	23.40	155	157	80.00	75.00
F	KENNARD	24.60	177	139	87.23	89.81
F	KENNARD	25.00	151	166	76.00	75.00
F	KENNARD	27.00	275	98	125.00	150.00
M	STRAUS	50.00	135	370		
F	TISHER <sup>3</sup>	23.87			67.10	
F	KENNARD	30.10				70.00
F	KENNARD	35.00				86.00
Mean		26.59 <sup>4</sup>	159	167	79.1 <sup>4</sup>	82.4 <sup>4</sup>

1 STRAUS, W. L. and ARCADI, J. A. [13].

2 KENNARD, M. A. and WILLNER, M. D. [8].

3 TISHER, C. C. [16].

4 Weights of last 3 animals not included.

In man renal functions reach the adult relationship to surface area by the age of two [8]. The ratio of kidney weight to total body weight in man [9, 10] is approximately 1:200, while that for the newborn is 1:138 (table II). The kidney of the chimpanzee increased in weight from infancy ( $2\frac{1}{2}$ –4 months) to prepubertal age by a factor of only 5.82, while in man there is nearly a thirteenfold increase in kidney weight from birth to adulthood (table II). Since the figure for the chimpanzee is not based on newborn or adult kidney weights, one cannot definitely conclude that this disparity in kidney growth is real. RIOPELLE has observed no growth spurt in the chimpanzee as is seen in man between the ages of 7 and 12 [11]. The age of the larger animals (group 4) is approximately 5–7 years old. This is equivalent to a 9–12 year old child, an age when renal functions, based on body surface area, have reached adult values. This would tend to suggest that a true difference in kidney growth, from infancy to adulthood, may exist between man and the chimpanzee.

STRAUS [12] does not believe that this difference can be attributed to the smaller birth weight (1.8 kg) of the chimpanzee.

*Table II.* Comparison of total body weight to kidney weight in man and chimpanzee

	Age	Body weight kg	Weight both kidneys g	Kidney weight Body weight	Adult kidney weight Newborn kidney weight
Man	Adults <sup>1</sup>	59.967	300	1 : 200	13.04
Man	Newborn <sup>1</sup>	3.175	23	1 : 138	
Chimpanzee Group 4 <sup>2</sup>		26.59	159	1 : 167	5.82
Chimpanzee Group 1 <sup>3</sup>		3.27	27.3	1 : 120	

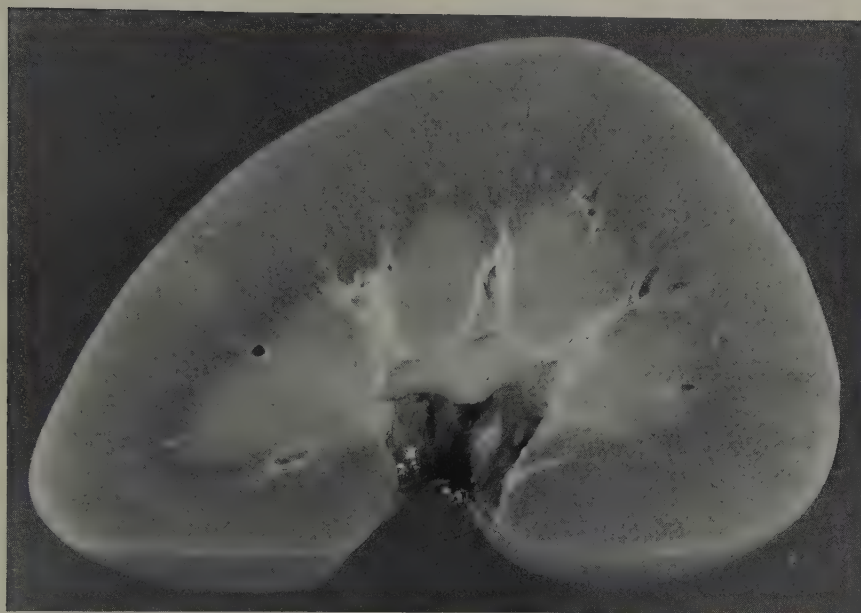
1 From STRAUS and ARCADI [1958].

2 Oldest group of animals in table I, approximate age: 5-7 years.

3 Infants, age: 2½-4 months; see table I.



*Fig. 2.* Photomicrograph showing the sagittal surface of the kidney represented in figure 1 after it was bivalved. Note particularly the four secondary or 'pseudo' pyramids which could be mistaken for true papillae. Courtesy of Dr. C. CRAIG TISHER.



*Fig. 3.* Photomicrograph showing the sagittal surface of the opposite half of the bivalved kidney represented in figures 1 and 2. The renal pelvic fascia and fat and the renal vessels have been removed to reveal the single distinct papillae in this kidney. Courtesy of Dr. C. CRAIG TISHER.

The question of whether the kidney of the chimpanzee is a single or multilobed organ was debated for a number of years. Division of the medulla by inward cortical projections called renal columns (Bertini) as occurs in man has not been widely reported in the chimpanzee. STRAUS [13] studied the pelvic surface of the medulla of eight chimpanzees by frontal section and observed either a simple papilla (unipapillate) or, of equal frequency, a flattening or concave surface without papilla formation. He did observe, however, 3–5 secondary papillae which he suggested could be mistaken for true papillae. SPERBER [14] studied four pairs of chimpanzee kidneys and similarly concluded that they were unipyramidal. He, likewise, felt that subdivisions of a single papilla could be mistaken for a multipapillate kidney. SYMINGTON [15] and TISHER [16] have also observed that the kidney of the chimpanzee was unipapillate (fig. 2, 3), while WOOD-JONES [17] has reported that although a single pyramid is the rule as many as seven may be present in the kidney of the chimpanzee.



## RENAL CLEARANCES

The renal clearance formula,  $UV/B$ , was first devised by ADDIS [18] in 1917 but it wasn't until 1929 that the term 'clearance' was applied to this formula by MOLLER, MACINTOSH and VAN SLYKE [19] in measuring the maximum amount of blood cleared of urea by the kidneys. In 1931, JOLLIFFE and SMITH [20] applied this term to the excretion of creatinine. And it is SMITH and his many associates who are generally credited with the development of modern renal clearance techniques to their present status as reliable measures of glomerular filtration and renal plasma flow.

A renal clearance is a quantitative measure of the ability of the kidneys to remove any solute which the kidney transfers from the blood to the urine. More specifically, it is the volume of plasma required to supply that quantity of a substance excreted each minute. To calculate such a clearance one needs only to know the rate of excretion of the substance in question and its simultaneous concentration in the plasma.

The symbols and method of calculation are as follows:  $V$  = rate of urine formation, in ml/min.  $U$  = concentration of the urinary constituent, in mg/ml.  $UV$  = rate of excretion in mg/min.  $P$  = concentration of the same substance in plasma, in mg/ml.  $C$  = plasma clearance of the named substance, in ml/min.  $C = \frac{UV}{P}$ . The rate of clearance of a substance, however, tells nothing about the mechanism of renal excretion. Each substance must fulfill certain criteria before its mode of renal handling can be ascertained.

The clearance of inulin, a fructose polysaccharide, was proposed as a measure of glomerular filtration in the early 1930's [21, 22] and it remains the choice standard of reference despite the introduction of numerous substances which are similarly handled by the kidney. Although there is no absolute proof that its clearance measures glomerular filtration, the following evidence strongly favors it as the most valid measure of filtration in all vertebrates. It is a large, inert molecule which is completely filterable at the glomerulus, is not metabolized by the body and is readily recovered in the urine following parenteral administration. One of the soundest criteria for the validity of measurements of glomerular filtration by any substance is the failure of changes in plasma concentration to alter the results, i.e., filtration is independent of plasma concentration. Of course these comparisons must be made under conditions where the actual rate of filtration can be presumed to be reasonably constant. Experience with man and many other animals has led to the conclusion that, except at very low rates of urine flow, glomerular filtration proceeds at a high and steady state.

More recently MARSH and FRASIER [23] have offered the most direct proof that inulin is neither secreted or reabsorbed between the proximal and distal tubule of the rat. The recovery of inulin was complete when it was introduced into the proximal tubule and collected in the distal tubule and systemic infusion of inulin using similar micropuncture techniques revealed no secretion.

## CLEARANCE OF INULIN

That the rate of excretion of inulin, in the chimpanzee, is independent of its concentration in the plasma has been reported by GAGNON and CLARKE [24]. Step-wise elevation of the plasma concentration of inulin from 25 to 122 mg% failed to alter its clearance (table III, Chimp. 2).

Table III. Renal clearances in the chimpanzee [from GAGNON and CLARKE, 1957]

Pe- riod	Urine flow	Plasma conc.			Clearance			Clearance ratio		Tubular secretion	Plasma conc.			Excretion		Reabsorbed fraction		
		Cr.	In	PAH	Cr.	In	PAH	In	PAH		Cr.	Na	K	Na	K	H <sub>2</sub> O	Na	K
ml min/m <sup>2</sup>		mg/100 ml			ml/min/m <sup>2</sup>			mg/min/m <sup>2</sup>				mEq/l		μEq/min		%		
<hr/>																		
Chimp. 1		♂	10.0 kg		Creatinine, inulin and PAH prime and sustaining													
1	4.0	14	6.9	0.8	76	58	257	1.30	0.23	1.7	2.4	141	3.6	15	11	93.2	99.7	90.1
2	7.2	13	7.5	0.9	77	65	239	1.18	0.27	1.7	1.5	143	3.6	29	10	89.0	99.4	88.8
Creatinine prime, more creatinine in sustaining																		
3	3.7	43	9.5	1.9	69	63	172	1.09	0.37	2.3	2.5	143	3.6	68	15	94.3	98.6	87.0
4	2.8	39	9.2	1.3	67	60	130	1.11	0.46	1.1	2.5	138	3.6	67	17	95.3	98.4	84.7
Creatinine prime, more creatinine in sustaining																		
5	2.1	62	10.0	1.5	62	58	118	1.08	0.49	1.1	2.9	138	3.6	52	16	96.3	98.8	85.0
6	3.3	61	10.0	1.0	67	64	121	1.04	0.53	0.7	1.7	138	3.5	52	12	94.8	98.9	89.8
7	2.4	58	9.7	0.7	66	63	113	1.04	0.56	0.4	1.4	138	3.5	58	16	96.3	98.7	85.8
<hr/>																		
Chimp. 2		♀	10.0 kg		Creatinine, inulin and PAH prime and sustaining													
1	3.8	18	25	2.1	81	65	215	1.25	0.30	3.5	3.0	129	3.6	37	24	94.1	99.6	90.0
2	4.1	18	25	2.2	82	65	211	1.26	0.31	3.5	3.0	129	3.6	41	26	93.8	99.5	88.8
Inulin prime, more inulin in sustaining																		
3	4.4	19	67	2.1	81	67	233	1.22	0.29	3.7	2.7	134	3.6	46	22	93.4	99.5	90.1
4	2.3	20	71	2.2	73	60	194	1.22	0.31	3.2	2.6	132	3.6	55	27	96.1	99.3	87.4
5	3.8	20	69	2.2	76	61	195	1.23	0.31	3.3	2.8	127	3.9	60	27	94.4	94.2	88.8

Table III. (Continued)

Pe- riod	Urine flow	Plasma conc.			Clearance			Clearance ratio		Tubular secretion	Plasma conc.		Excretion		Reabsorbed fraction			
		Cr.	In	PAH	Cr.	In	PAH	In	PAH		PAH	Cr.	Na	K	Na	K	H <sub>2</sub> O	Na
ml min/m <sup>2</sup>		mg/100 ml			ml/min/m <sup>2</sup>			mg/min/m <sup>2</sup>			mEq/l		μEq/min		%			
Inulin prime, more inulin in sustaining																		
6	1.5	20	106	2.0	70	57	209	1.23	0.27	3.3	2.6	127	3.5	20	22	97.3	99.7	89.2
7	1.5	20	108	2.1	79	66	234	1.20	0.28	3.8	2.7	127	3.5	14	27	97.7	99.8	88.3
8	0.3	20	114	2.0	68	55	206	1.24	0.22	3.4	2.6	127	3.4	12	23	99.6	99.8	87.8
9	2.8	21	122	2.1	82	61	245	1.34	0.19	4.2	4.4	127	3.4	29	29	95.4	99.6	86.5
Chimp.3 ♂ 7.5 kg Creatinine, inulin and PAH prime and sustaining																		
1	6.8	11	14	0.9	100	71	312	1.41	0.23	2.3	3.3	138	3.7	9	9	90.5	99.8	91.8
2	4.4	11	15	0.9	100	67	290	1.49	0.20	2.5	3.6	138	3.7	11	12	94.5	99.7	88.9
PAH prime, more PAH in sustaining																		
3	5.0	12	19	18	86	63	209	1.36	0.22	44	2.7	135	3.5	76	26	93.6	98.0	72.4
4	4.4	13	19	18	82	65	158	1.26	0.25	40	2.1	134	3.8	71	28	94.1	98.1	74.2
PAH prime, more PAH in sustaining																		
5	4.8	15	20	73	73	65	143	1.11	0.45	65	1.1	138	4.1	154	33	93.1	95.9	71.1
6	4.5	15	20	77	73	63	147	1.15	0.45	67	1.5	138	4.1	158	34	94.2	95.8	69.1
7	4.0	15	19	76	67	58	137	1.16	0.42	67	1.4	138	3.8	142	33	94.8	95.9	65.2
Chimp.4 ♀ 14.0 kg Creatinine and inulin prime and sustaining																		
1	2.7	15	18		111	76		1.46			5.1	138	2.5	61	52	96.5	99.4	72.7
2	3.3	14	18		123	86		1.42			5.1	136	2.4	141	61	96.2	98.8	70.8
3	3.2	14	17		106	80		1.34			3.7	135	2.7	184	53	96.0	98.3	75.0
Probenecid prime and added to sustaining																		
4	3.8	15	19		102	85		1.19			2.5	133	2.8	116	54	95.5	99.0	74.1
5	5.1	15	19		106	89		1.20			2.6	131	2.7	285	76	94.3	97.6	67.9
6	6.9	15	18		113	98		1.16			2.3	133	3.1	424	84	93.0	96.7	71.9
PAH prime and added to sustaining																		
7	6.1	14	16	37	102	86	174	1.19	0.49	37	2.3	138	2.4	365	90	93.0	96.7	61.9
8	6.3	14	16	42	100	84	162	1.19	0.52	38	2.2	130	2.6	502	100	92.5	95.4	55.0
9	6.7	14	15	48	91	81	139	1.13	0.59	34	1.5	131	3.2	608	109	91.8	94.3	57.7
Chimp.5 ♂ 13.1 kg Creatinine and inulin prime and sustaining																		
1	5.4	13	18		161	103		1.57			7.7	140	2.3	51	35	94.7	99.6	85.4
2	3.9	13	17		145	98		1.48			6.1	140	2.3	93	54	96.0	99.3	76.5
3	4.2	13	17		161	108		1.49			6.6	142	2.3	106	62	96.1	99.3	75.5
PAH prime and added to sustaining																		
4	6.8	13	17	98	91	69	145	1.32	0.47	84	2.9	145	2.3	59	67	90.1	99.4	57.3
5	8.0	13	17	98	95	77	152	1.25	0.50	86	2.5	145	2.3	77	96	89.6	99.3	45.3
6	7.1	13	17	100	93	70	147	1.34	0.47	87	3.1	144	2.3	71	110	89.9	99.3	31.7

In 1938, SMITH and CLARKE [25] measured, for the first time, the clearance of inulin (19 periods) in three young female chimpanzees and found it to average 98 ml/min/m<sup>2</sup> (table IV). In the later study [24] the clearance of inulin (35 periods) was measured in three male and two female, immature animals. It averaged 79 ml/min/m<sup>2</sup> (range 61–100) or 3.9 ml/min/kg. HAMLIN, SMITH and CARTER [26] more recently have measured the clearance of inulin (22 periods) in nine, young, anesthetized chimpanzees. They obtained an average clearance of 2.9 ml/min/kg.

Table IV. Glomerular filtration, effective renal plasma flow and renal fraction in the immature chimpanzee

Animal Sex	Body weight kg	Surface area m <sup>2</sup>	No. pe- riods	CIn ml/min/m <sup>2</sup>	CIn ml/min/kg	CPAH ml/min/m <sup>2</sup>	CPAH ml/min/kg	F.F. CIn/CPAH	Renal fraction <sup>1</sup> %
Group 1 [SMITH and CLARKE 1938]									
Babe F		0.522	6	133					
Peggy F		0.892	6	73					
Lucy F	36	1.19	7	89					
Mean		0.87		98					
Group 2 [GAGNON and CLARKE 1957]									
Chimp. 1 M	10.0	0.520	7	61	3.2	248	12.9	0.25	
Chimp. 2 F	10.0	0.520	9	62	3.2	213	11.1	0.29	
Chimp. 3 M	7.5	0.429	7	65	3.7	301	13.7	0.22	
Chimp. 4 F	14.0	0.650	9	85	3.9				
Chimp. 5 M	13.1	0.622	3	101	4.8				
Chimp. 5 M	13.1	0.622	2	98	4.7	296	14.0	0.33	
Mean	11.3	0.560		79	3.9	265	12.9	0.27	
Group 3 [HAMLIN, SMITH and CARTER 1964]									
178	26.8		2	2.2			12.0	0.26	14
177	22.7		2	2.2			10.6	0.21	11
171	17.3		2	2.3			11.6	0.20	11
157	17.3		2	2.4			11.7	0.20	12
194	12.7		3	2.8			15.1	0.19	13
169	14.1		3	3.9			15.9	0.25	18
204	15.0		3	3.1			13.8	0.22	15
168	14.5		3	3.9			15.3	0.26	18
190	15.0		2	3.2			14.9	0.21	15
Mean	17.3			2.9			13.4	0.22	14

1  $\frac{\text{Effective renal blood flow} \times 100}{\text{cardiac output}}$



The body weight of the second group of animals (table IV) is significantly less than that of the third group yet the clearance of inulin is greater. This suggests that the rate of glomerular filtration per body weight in the larger animals (table I) is directly related to the ratio of kidney weight/body weight, as is the case in man. Because of the small number of investigations however one cannot dismiss the possibility of discrepancies in the inulin analyses.

Since the total number of animals is too small to permit subdivision by sexes the establishment of a mean GFR value for each sex must also await the collection of more data.

Because of the nature of these animals, anesthesia was used in all of the experiments; sodium pentobarbital or sodium amytal [24], sodium pentobarbital [23] and phencyclidine hydrochloride followed by either sodium thio-penthal or pentobarbital [25]. Further studies are required to determine whether the absolute values of glomerular filtration may have been modified by the use of these anesthetic agents. With the more sophisticated methods of restraint being utilized in the studies of large primates today, this kind of information should be available soon.

#### FILTRATION FRACTION

That portion of the plasma perfusing the kidney which is excreted only by filtration through the glomeruli is known as the filtration fraction. To calculate this fraction one has only to measure glomerular filtration ( $C_{in}$ ) and renal plasma flow ( $CPAH$ ) simultaneously. The fraction is a ratio of  $C_{in}/CPAH$ .

The average filtration fraction in the chimpanzee has been found to be 0.22 [25] and 0.27 [23]. If one corrects the  $C_{in}$  for the presence of approximately 8% plasma protein (only protein-free water is filtered) and the  $CPAH$ , based on an extraction of approximately 90%, then the filtration fraction would approximate 0.20. The mean filtration fraction for normal man is  $0.19 \pm 15\%$ .

#### CLEARANCE OF CREATININE

REHBERG [27] in 1926 first proposed that the excretion rate of exogenous creatinine could be used as a measure of glomerular filtration. It was not until later that creatinine was found to be not only filtered but excreted by the tubules in the fish, frog, reptile, bird, guinea pig, rat, monkey, ape and man.

The evidence for the tubular secretion of creatinine, which would also apply to any other substance similarly handled by the kidney is: 1. The creatinine/inulin clearance ratio at low plasma levels is above one. 2. The clearance of creatinine is depressed both absolutely and relative to the clearance of inulin when the plasma concentration of creatinine is elevated. 3. Administration of such drugs as phlorizin or probenecid [28], whose action is known to inhibit tubular secretory activity, lowers the creatinine/inulin ratio. 4. Administration of large doses of p-aminohippurate, which is largely excreted by the renal tubules, depresses the creatinine/inulin ratio to near one in man, suggesting a common mechanism for the tubular excretion of creatinine and PAH [29].

SMITH and CLARKE [25] first proposed that creatinine was partially excreted by the renal tubule of the chimpanzee. They observed a creatinine/inulin ratio significantly above one in three animals. Elevation of the plasma creatinine level from 14 to 100 mg% lowered this ratio from 1.24 to 1.0. The precise means by which the secretion of one substance by the renal tubules is linked to that of another is not well understood but the effects of competition for secretion has been well demonstrated. When the plasma level was allowed to fall to 30 mg% the ratio promptly rose to 1.32. Administration of phlorizin abolished the difference between the two clearances. In 1944 these conclusions were challenged by EKEHORN [30] who postulated a variable tubular reabsorption of inulin.

In 1957 additional evidence was reported [24] which firmly established the fact that creatinine is excreted by the renal tubules of the chimpanzee (table III). Loading the kidney with creatinine depressed the creatinine/inulin ratio while similarly loading with inulin had no such effect (Chimp. 1 and 2). Further evidence was presented which showed the effect of materials known to be secreted or to affect tubular secretion on the creatinine clearance. The Ccr was sharply depressed when p-aminohippurate was present in large amounts in the plasma while the C<sub>in</sub> remained unaffected (Chimp. 3). The administration of probenecid, which interferes with tubular secretory activity, also lowered the Cr/In ratio from 1.41 to 1.18. In two experiments in which PAH was completely absent from the blood the Ccr/C<sub>in</sub> ratios averaged 1.41 and 1.51. At low PAH concentrations the ratios were 1.24, 1.26 and 1.45, suggesting that even below 2 mg % in plasma, PAH exerts a competitive or suppressing action on creatinine secretion in this animal.

It would appear, therefore, that, like man, the chimpanzee excretes significant quantities of creatinine by a tubular secretory process. This makes the clearance of exogenous creatinine an unacceptable measure of glomerular filtration in this animal.

## ENDOGENOUS CREATININE CLEARANCE

The apparent clearance of endogenous creatinine is not an exact measure of glomerular filtration in man despite the fact that its clearance has often been reported to approximate the  $C_{in}$ . In addition to it being secreted, there is present in the plasma a non-creatinine chromogen which is only partially excreted in the urine. This results in a lower clearance of the non-creatinine fraction giving an erroneously lower total chromogen clearance. As PITTS [31] has pointed out, the agreement often observed between the clearances of endogenous creatinine and inulin in man presumably results from the balance of these two errors: tubular secretion of creatinine and the presence of non-creatinine chromogens in the plasma.

The clearance of endogenous creatinine was measured in six chimpanzees prior to the urinary clearances of exogenous creatinine and inulin [24]. For the analyses plasma proteins were precipitated with trichloroacetic acid. The mean clearance was 2.36 ml/min/kg while the clearances of exogenous creatinine and inulin, obtained immediately thereafter were 5.68 and 4.0 ml/min/kg, respectively. The ratio of the clearance of endogenous creatinine to inulin averaged 0.59 while the ratio of exogenous creatinine to inulin was 1.42. The apparent plasma creatinine concentration was 0.73 mg % (range 0.6–1.0).

LAYNE *et al.* [32] have reported twenty-four hour urinary creatinine excretion rates on six immature chimpanzees averaging 15.5 kg body weight. These animals excreted an average of 323 mg per day.

An hourly excretion rate of approximately 20 mg endogenous creatinine has been reported by ELMADJIAN [33] in a group of chimpanzees weighing approximately 40 lb. No plasma creatinine values were given.

The urinary excretion of endogenous creatinine was measured by SCOTT [34] in 20 immature chimpanzees while restrained in the sitting position for 24 h. The bladder was catheterized and urine specimens collected at six-hour intervals. Clearances of 2.41 and 1.52 ml/min/kg in males and females, respectively, were obtained during the first 6 h and declined to 2.02 and 1.45 ml/min/kg during the last six-hour period. Since this type of restraint appears to offer the only means by which many studies can be performed in this animal in the conscious state, it is imperative that its effects on function be thoroughly investigated.

The excretion of endogenous creatinine was examined in three immature chimpanzees while on a creatinine-free diet of bananas, wheat bread and 'Chimcrackers' [35]. For comparison of results, the urine of two normal human subjects, restricted to the same diet, was similarly analyzed. The calculated

creatinine coefficient of two male chimpanzees averaged 11.8 mg/kg/day while the one female excreted 9.6 mg/kg/day. The human subjects excreted only 7.1 mg/kg/day suggesting a high endogenous creatinine metabolism in the sub-human primate.

SMITH and CLARKE [25] found the creatinine coefficient to be 30 mg/kg/day in one chimpanzee not maintained on a creatinine-free diet, but the calculation of this value was based on the excretion of creatinine during one short urinary collection period.

It would appear from these observations that the endogenous creatinine clearance is significantly less than the inulin clearance. There appears to be no 'balancing of errors' in this limited number of observations. This may be the result of a smaller proportion of the non-creatinine plasma chromogen appearing in the urine of this animal.

#### UREA EXCRETION

Urea is the chief nitrogenous end product of protein metabolism and normally the major urinary solute. For many years it was generally thought of as one of the least functionally important constituents of the urine. However, with the development of the countercurrent concept for the urinary concentrating process [36], urea has been found to play a major role in the excretion of a maximally concentrated urine.

Although the plasma concentration of urea is not quantitatively a reliable index of renal function since it varies with the rate of production and the rate of excretion it has been a valuable diagnostic indicator; early clinicians often relied on the excretion of urea as a useful, non-quantitative, standard reference.

Since urea is completely filterable yet its clearance is always below the clearance of inulin, some of the filtered urea must disappear from the tubular lumen. It is generally held that the portion which escapes excretion is passively diffused down a concentration gradient in most mammals. The rate at which it diffuses is related to the urine flow. In man, the urea clearance which averages 75 ml/min/1.73 m<sup>2</sup> is relatively stable at a urine flow above 1.5 to 2 ml/min [19].

The average urea clearance in nine chimpanzees was found [26] to average 1.8 ml/kg/min which was 62 % (range 56–67 %) of the inulin clearance (table V). In normal man, at random urine flows, the per cent of filtered urea excreted was found to average 63 % [22, 37].



Table V. Urea clearance and tubular transport of glucose and P-aminohippurate in the chimpanzee<sup>1</sup>

Animal	Urea clearance ml/kg/min	Urea clearance	TmPAH mg/kg/min	TmGlucose mg/kg/min	C <sub>in</sub>	C <sub>PAH</sub>
		Inulin clearance			TmPAH	TmPAH
178	1.5	67	0.83	9.3	2.65	14.46
177	1.3	60	1.87	12.0	1.18	5.67
171	1.3	56	1.60	17.0	1.44	7.25
157	1.4	59	1.02	15.6	2.35	11.47
194	2.0	69	0.93	8.9	3.01	16.23
169	2.3	60	1.37	17.3	2.85	11.61
204	2.0	65	0.97	14.8	3.20	14.23
168	2.2	56	0.97	18.1	4.02	15.77
190	2.0	62	1.03	15.4	3.11	14.47
Mean	1.8	62	1.18	14.26	2.65	12.35

1 From HAMLIN, SMITH and CARTER [1964].

ELMADJIAN [33] measured 24-hour urinary urea excretion rates in 5 normal, 40 lb chimpanzees. Each daily collection was divided into 2 samples representing a day and a night period. The day specimen averaged 178 mg/h and the night specimen 201 mg/h. Plasma urea averaged 14.6 mg % (range 9.9–17.1). From these data the calculated urea clearance averages 1.3 ml/kg/min. Urine flow was not reported but one might suspect from the low urea clearance that it was low.

The urinary excretion of urea nitrogen by three chimpanzees maintained on a low protein diet for one week was 1.79, 2.27 and 1.61 g/day or 0.066 mg/kg/min [35]. Two human subjects on the same diet of milk, chimcrackers and bananas for four days prior to the test excreted 6.92 g/day or 0.081 mg/kg/min.

#### TUBULAR SECRETION

When the clearance of a substance, which is not synthesized by the kidneys, is greater than the simultaneous clearance of inulin, it may be accepted that it is excreted by the tubule in addition to being filtered. It does not necessarily

follow, however, that the excretion of a substance which equals the excretion of inulin be by filtration only, for the tubules also have the ability to reabsorb.

Tubular secretory mechanisms transport material from peritubular fluid to the tubular lumen or from the lumen back into the interstitial fluid from whence the solutes diffuse back into the blood stream. If the substance is transported against an electrochemical gradient, thereby requiring a continuous supply of oxygen, this must be an active form of secretion.

If in transit through the kidney a substance,  $X$ , is completely removed from the plasma by filtration and tubular secretion, the rate of excretion ( $U_X V$ ) divided by the plasma concentration ( $P_X$ ) will be equal to the volume of plasma perfusing the glomeruli and tubules per unit of time. If renal extraction is incomplete the clearance will be less than the renal plasma flow (RPF). Para-aminohippurate (PAH) is the most commonly used compound in estimating renal plasma flow since approximately 90 % of the compound is removed from the blood during its transit through the kidney in man. If the extraction of PAH ( $E_{PAH}$ ) is known a measure of all the plasma moving between the renal artery and renal vein can be obtained by dividing the  $C_{PAH}$  by the  $E_{PAH}$ .

Since any plasma solute secreted by the renal tubules is also filtered, the rate of tubular excretion,  $T_X$ , must be the difference between the total rate of excretion,  $U_X V$ , and its filtration rate.<sup>2</sup>

Tubular secretion is usually limited by a maximal rate of tubular transport. As the plasma concentration,  $P_X$ , is increased, tubular secretion increases proportionally until the tubular transport mechanism becomes loaded to capacity. This maximum rate of secretory transport is designated as  $T_{mx}$  and is a commonly used index of tubular function.

#### CLEARANCE OF P-AMINOHIPPURATE ( $C_{PAH}$ )

HAMLIN, SMITH and CARTER [26] have measured the clearance of p-aminohippurate, a measure of effective renal plasma flow (ERPF) in nine chimpanzees and found it to average 13.4 ml/min/kg (table IV). In a group of smaller animals (table IV, group 2) the  $C_{PAH}$  averaged 12.9 ml/min/kg. It is surprising that there is so little difference between these two groups since there is such an appreciable difference in weight, and presumably age. It may be that renal

2 In computing  $T_{PAH}$  the filterable fraction ( $F$ ) of PAH must be assessed as it, unlike inulin, is partially bound to plasma protein thereby making it unavailable for filtration. The water content of the plasma ( $W$ ) must also be considered in the calculation. Therefore, the complete formula is:  $T_{PAH} = U_{PAH} V - P_{PAH} \times C_{in} \times FW$ .

plasma flow in the animals in the second group (approximate age  $3\frac{1}{2}$  years) has nearly reached adult values on a body weight or surface area basis.

MEEHAN, HENRY and FINEG [38] measured the effective renal blood flow, using p-aminohippurate, in chimpanzees during spontaneous alterations in arterial blood pressure. The changes occurred while training the animal to learn to perform a complex psychomotor task. The average blood flow for all observations was 560 ml/min for a 25 kg animal. The flows tended to be higher at the lower pressures. The highest flow obtained was 38 ml/min/kg at a pressure of 135/70 mm Hg while the lowest flow of 11.6 ml/min/kg was measured at a pressure of 180/120 mm Hg. It was concluded that these observations were consistent with those made in the young hypertensive human with a labile blood pressure.

#### RENAL FRACTION

The kidneys of a normal man at rest are perfused with a volume of blood equivalent to approximately 20% of the cardiac output. HAMLIN *et al.* [26] have measured the effective renal fraction, i.e., CPAH divided by the cardiac (plasma) output, in the chimpanzee and found it averaged 14% (table IV). Correction of this value for a 90% extraction of PAH would raise the renal fraction to 15.7%.

#### FUNCTIONAL MEASURE OF TUBULAR SECRETORY ACTIVITY

When the plasma concentration of a substance such as p-aminohippurate or glucose is raised to 30 and 300 mg%, respectively, the secretory cells of the proximal tubule become saturated, i.e., the rate of secretion remains constant with any further increase in plasma concentration. Smith introduced the term 'tubular maximum', symbolized  $T_m$ , to denote this maximum rate expressed in milligrams per minute, at which the tubular cells can transfer their appropriate substance. The  $T_{mPAH}$  is conventionally used today as a quantitative measure of functional tubular tissue.

GAGNON and CLARKE [24] have reported the  $T_{PAH}$  in three chimpanzees to be 34, 67 and 87 mg/min/m<sup>2</sup> or 1.67, 4.0 and 4.38 mg/min/kg at plasma levels of 48, 76 and 100 mg% PAH, respectively (table III). They did not suggest these values represented true tubular maxima since titration curves were not obtained to show that further elevation of PPAH would not have raised

the TPAH even further. It appears safe to assume, however, that the latter two values are actually Tm's in these animals.

If the plasma concentration of PAH is raised to excessively high levels (20 to 40 mg %) in the determination of Tm in the dog or cat secretory transport may cease; the amount excreted then can be used to calculate glomerular filtration provided a correction is made for the protein bound fraction. This phenomenon is not observed in man and one might conclude from the above data, at least from Chimp. 3 and 5, that self-depression of secretory transport is similarly absent in the chimpanzee.

HAMLIN [26] has calculated TmpAH in nine chimpanzees and found it to average 1.18 mg/kg/min at a plasma concentration of 15–19 mg % (table V). Since the plasma levels were not raised above the initial values, one cannot be sure that they represent true tubular maxima.

The average TmpAH in normal human subjects is generally found to approximate 75–80 mg/min/1.73 m<sup>2</sup> of body surface [31, 39].

The size of the kidneys and therefore the quantity of functional tissue has been shown to vary widely in normal man. Therefore, it is appropriate to refer both the effective renal plasma flow and the filtration rate to the total quantity of functional tubular tissue as measured by the saturation method. In man the CPAH/TmpAH ratio has been found to average 8.15 and the C<sub>in</sub>/TmpAH 1.5 [40]. In the chimpanzees these ratios are reported as 12.35 and 2.65 (table V).

#### TUBULAR REABSORPTION OF GLUCOSE

In 1924, WEARN and RICHARDS [41] demonstrated that the tubules of the frog kidney reabsorb glucose. In 1933 WALKER and REISINGER [42] confirmed this observation when they found the concentration of glucose in the glomerular filtrate to be identical to that in the plasma in the absence of glucosuria. This reabsorptive process has been shown, by stop-flow and micropuncture studies, to occur in the proximal tubule.

When the plasma concentration of glucose is elevated above a critical level, often referred to as the renal 'threshold', glucose will be excreted in the urine. To measure the rate of tubular reabsorption of glucose, Tm, (mg/min) under such a condition, one needs only to calculate the difference between the rate of filtration of glucose and the rate of its excretion in the urine, UGV. Therefore  $TG = PG \cdot GFR - UGV$ , where PG is the plasma concentration of glucose in mg/ml, V is the urine flow in ml/min and UG is the urine glucose concentra-



tion in mg/ml. Further elevation in plasma glucose beyond that point at which the capacity to reabsorb is fully saturated, the reabsorption of glucose reaches a constant, maximal rate, TmG. In man, the capacity to reabsorb glucose averages 375 and 300 mg/min/1.73 m<sup>2</sup> of body surface area, in men and women, respectively [40].

HAMLIN [26] reports the TmG in nine, normal, immature chimpanzees averaged  $14.26 \pm 3.39$  mg/kg/min. Since the mean filtration rate in this group of animals was 2.9 ml/kg/min, it is apparent that a plasma glucose concentration of nearly 5.0 mg/ml would be required to completely saturate the reabsorptive mechanism for glucose. Assuming a plasma glucose concentration of 1.0 mg/ml [33] the filtered load is equal to only one-fifth of the TmG. Hence, one might expect that the filtration rate could be increased fivefold without producing glycosuria. In actual practice, however, this is not the case. Since all tubules are not anatomically or functionally identical saturation of all tubules is not achieved simultaneously so an increasing quantity of filtered glucose escapes tubular reabsorption as the TmG is approached.

#### URIC ACID EXCRETION

Although the urinary excretion of uric acid is still not completely understood, the most widely held view is that in humans uric acid is filtered at the glomerulus, completely or nearly completely reabsorbed in the proximal tubule and partially secreted in the distal tubule. The normal adult excretes approximately 650 mg/day or 0.45 mg/min on a normal purine diet. At an average plasma level of 5 mg %, the uric acid clearance in such an individual would be 9 ml/min or 0.13 ml/kg/min. At a filtration rate of 125 ml/min the daily filtered load would approximate 9 g. This means that only 7 % of the filtered load is excreted.

ELMADJIAN [33] has examined the urinary excretion of uric acid in a group of young (18.2 kg B.W.) chimpanzees. They excreted an average of 348 mg/day or 0.267 mg/min. No plasma urate concentrations were reported. Assuming a plasma level of 2 mg %, <sup>3</sup> the uric acid clearance would be 13.3 ml/min or 0.73 ml/kg/min.

RHEINBERGER [35] has reported the daily excretion of 3.8 mg/kg of uric acid by three chimpanzees maintained on a purine-free diet for one week while two

3 Plasma uric acid in six normal chimpanzees averaged 2.0 mg % as determined by the automated uric acid procedure adapted from the method described in *Practical Physiological Chemistry* by HAWK, OSER and SUMMERSON, 13th ed., p. 564.

human subjects, on the same diet, excreted 2.2 mg/kg/day. Since uric acid is the end product of purine metabolism derived partially from dietary purine a low urinary clearance of uric acid might be anticipated.

#### WATER AND ELECTROLYTE EXCRETION

The volume and composition of the body fluids in mammals are held remarkably constant over a wide range of water and solute intake. This is attributed to the development of a countercurrent multiplier system in the kidney which salvages water by concentrating the urine and a mechanism for the control of the water reabsorptive processes in the kidney which operates through the hypothalamus and posterior lobe of the pituitary. For control of body sodium man possesses a mechanism which regulates renal salt reabsorption through the adrenal cortex.

As the blood flows through the glomerular capillaries in man about one-fifth of the plasma water passes through the membranes of the capillaries and glomerulus and enters the proximal portion of the renal tubule. All the major ions including sodium, potassium, chloride and bicarbonate pass freely through the glomerular membranes with this water. Therefore, these substances appear in the filtrate at approximately the concentration at which they exist in the plasma water.

In the tubule both solute and water transport take place by two processes which denote only direction and not the mechanism of transport. Materials such as water, sodium, potassium, chloride, and bicarbonate which are transported across the tubular epithelium from the lumen of the tubule to the interstitial fluid and thence to the blood of the peritubular capillaries are said to be reabsorbed. Transport of materials such as potassium and hydrogen ions, from the peritubular blood to the interstitial fluid, across the tubular epithelium and into the lumen, is said to be by secretion.

*Water excretion.* That fraction of filtered water which is normally reabsorbed between the glomerulus and the bladder in man totals approximately 98–99 %. This means that at a glomerular filtration rate of 125 ml/min only 1800 to 3600 ml of the 170 l of water<sup>4</sup> filtered in 24 h is excreted. Approximately 80 % of this filtered volume is passively reabsorbed in the proximal tubule. As sodium salts are actively reabsorbed in this portion of the tubule the contents becomes

4 Since plasma is approximately 94 % water (6 % protein) in man the rate of glomerular filtration of water is calculated as:  $GFR \times (100 - 6\%) / 100$ .

hypotonic to its surroundings. In response to this osmotic gradient water follows the salts out of the tubule leaving the proximal tubular fluid isotonic to the blood. Thus this process which removes by far the greatest fraction of filtered water does so without influencing the concentration of the excreted urine.

Under normal conditions the urine is somewhat hypertonic to the blood and the flow rate is low, ranging from 0.016 to 0.032 ml/kg/min in an 80 kg man.

Changes in the osmotic pressure of the blood resulting in the inhibition or release of antidiuretic hormone (ADH) determine whether a dilute or concentrated urine is to be produced. An increase in the osmotic pressure of the blood, due to a water loss or solute gain, stimulates the release of ADH from the posterior lobe of the pituitary gland. In the presence of this hormone the convoluted tubule and collecting duct become permeable to water leading to the elaboration of a concentrated urine. This disproportionate loss of water to solute tends to restore the solute concentration of the body fluids to normal. On the other hand, a decrease in blood osmolality, due to excessive water intake or solute loss, inhibits the release of ADH which, in turn, decreases the permeability of the distal convoluted tubule and collecting duct to water. A dilute urine containing an excess of water is then excreted ultimately returning the osmotic pressure of the body fluids to normal.

A number of studies have been reported in which the urinary excretion of water has been measured under a variety of conditions in the chimpanzee. The mechanisms by which he is able to maintain homeostasis in the face of changes in the volume and solute concentration of his body fluids, however, can only be inferred because of the nature of these experiments.

The urinary flow rate of a group of anesthetized, supine chimpanzees [24] averaged 4.4 ml/m<sup>2</sup>/min or 0.22 ml/kg/min during the infusion of creatinine, inulin and p-aminohippurate (table III). At a filtration rate of 45 ml/min 94 % of the filtered water was reabsorbed. The quantity of non-reabsorbable solutes infused undoubtedly is responsible for the excretion of such a large fraction of the filtered water. When urinary excretion rates were measured in a group of 9 animals over a three-day period they averaged 0.025 ml/kg/min, a value very similar to that of normal man [26]. The specific gravity of the urine averaged  $1.025 \pm 0.006$ . Feeding and watering were done individually by hand to prevent spillage (table VI).

LAYNE *et al.* [32] collected twenty-four hour urine volumes on four chimpanzees housed in large metabolic cages. Food and water were not restricted. An average of 1024 ml/day or 0.043 ml/kg/min was excreted.

In a study designed to identify alterations in plasma and urinary constituents associated with twenty-four hours of chair-restraint, SCOTT [34] collected

*Table VI.* Water and electrolyte excretion in the chimpanzee<sup>1</sup>

Animal	Volume ml/kg/day	Na mEq/kg/day	K mEq/kg/day	Cl mEq/kg/day	pH	Specific gravity
194	33.46	1.11	0.76	1.08	7.0	1.024
157	65.70	1.34	1.36	1.43	8.2	1.024
204	46.21	1.49	1.18	2.64	6.8	1.030
190	49.57	1.98	1.05	2.90	7.0	1.020
168	45.57	1.89	1.00	2.35	9.0	1.022
169	41.20	1.60	0.92	2.18	7.4	1.014
178	5.02	0.38	0.57	0.48	7.6	1.032
177	14.23	0.63	0.86	0.74	7.6	1.022
171	17.01	0.48	0.93	0.49	7.0	1.030
Mean	35.33	1.21	0.96	1.59	7.3	1.025

1 From HAMLIN, SMITH and CARTER [1964].

urine specimens every 6 hours from a group of 20 chimpanzees. Food and water were offered. In the first six hours the males excreted an average of 0.07 ml/kg/min while the females excreted 0.04 ml/kg/min. During the last six-hour period they excreted 0.043 and 0.039 ml/kg/min, respectively. These flow rates do not suggest that chair restraint for one day results in any marked increase in ADH secretion.

ROHLES [43], desirous of determining the stress of social isolation for 30 days, measured the daily urinary output of 3 immature chimpanzees housed in small test chambers. They were restrained in chairs and provided with food and water for which they had to work. Despite a loss of one-half to two pounds of body weight they excreted an average of 0.4 ml/min or 0.026 ml/kg/min.

When ARCHIBALD and WARD [44] subjected five chimpanzees to an environment of 80° F and 50% humidity for 24 h while depriving them of food and water the urine volume declined from 0.042 to 0.008 ml/kg/min. They lost an average of 5.4% of their body weight. Urine osmolalities were not measured but the severe state of dehydration was confirmed by the specific gravity which increased from 1.013 to 1.031. The capacity to concentrate the urine to such an extent in man is similarly reflected in the weight response (loss) to water deprivation. The loss of up to 7% of body weight during 84 h of dehydration in a group of 12 normal adults resulted in the excretion of a urine whose specific gravity rose from 1.012 to 1.037 [45].



ISAACSON [46] reported that 90 % of a group of 63 normal, human subjects attained urinary osmolalities of over 900 mOsm/l after an 18-hour period of fluid deprivation. The mean was 1027 mOsm/l.<sup>5</sup>

Determination of the specific gravity of the urine after a period of fluid restriction has been widely used as an indirect indication of the concentrating power of the kidney. ADDIS and SHEVKY [47] reported an average specific gravity of 1.032 in 75 normal subjects deprived of water for 24 h.<sup>6</sup>

#### REABSORPTION AND EXCRETION OF SODIUM AND CHLORIDE

Long before the theory of urine secretion embodying the processes of filtration, reabsorption and secretion was known, CLAUDE BERNARD observed that the environment in which we live is the blood and body fluids that bathe our tissues and that the constancy of its composition enables us to live a free and independent life. Today it is general knowledge that the kidney is primarily responsible for the regulation of this environment. Since sodium salts constitute more than 90 % of the solute of the extracellular fluid, one of its major tasks is the recovery of more than 99 % of the filtered sodium in maintaining homeostasis. Approximately 80 % is actively reabsorbed in the proximal tubule accompanied by the passive diffusion of chloride ions. As a result of this movement of ions out of the lumen an osmotic force is created resulting in the diffusion of an equivalent amount of water from the proximal tubule. The remaining sodium is actively reabsorbed in the ascending limb and distal convoluted tubule. Its reabsorption here is not necessarily accompanied by the reabsorption of an anion. It may be replaced or exchanged for potassium, hydrogen or ammonium ions. The reabsorption of chloride in the distal tubule

5 The urinary flow rate in 3 immature chimpanzees, deprived of fluid for 36 h, averaged 0.072 ml/min. Six one-hour urine collections were obtained on each animal. The urine osmolalities of the six pooled specimens were 1365, 1170, and 904 mOsm/kg water. Plasma osmolalities were not determined in these 3 animals but in another animal it was 305 mOsm/kg water. Assuming this to be representative of the 3 deprived animals the osmotic U/P ratios would be 4.5, 3.8 and 3.0. These values probably do not represent maximally concentrated urines since the 36 h of fluid restriction probably decreased glomerular filtration resulting in decreased delivery of solute to the distal tubule. Failure to maintain a normal protein intake would also lead to a reduction in the concentrating ability of the kidney. The maximal U/P ratio in man deprived of water for twelve hours is approximately 4.0.

6 The mean specific gravity after 36 h of fluid deprivation in 3 chimpanzees was 1.030 (1.023–1.040).

is not clearly understood but there is evidence to suggest that it may be actively reabsorbed. In the process of this tubular recovery of sodium, especially in the ascending limb of Henle, the medullary interstitium becomes increasingly hypertonic from the corticomedullary junction to the tip of the papilla. The pumping of sodium out of this water impermeable limb and into the medullary interstitium is the prime determinant in the development of this gradient which in turn is ultimately responsible for the elaboration of a concentrated urine.

The rate of sodium excretion is influenced by a number of factors including changes in glomerular filtration, alterations in circulating levels of adrenal cortical hormones, especially aldosterone and by an increase in the filtration of poorly reabsorbable solutes. In addition, there is an undetermined mechanism which results in a decrease in proximal tubular sodium reabsorption following the administration of saline solutions.

Estimates of sodium and chloride intake and urinary output by the chimpanzee over a three-day period have been reported by HAMLIN and his colleagues [26]. On a daily intake of  $0.64 \pm 0.41$  mEq/kg of sodium and  $1.17 \pm 1.0$  mEq/kg chloride these animals excreted  $1.21 \pm 0.44$  and  $1.59 \pm 0.95$  mEq/kg/24 h, respectively. The daily urinary excretion of sodium and chloride in normal man (70 kg B.W.) is about 111 and 119 mEq [48], or approximately 1.6 and 1.7 mEq/kg/24 h. The authors suggested that the discrepancy between intake and output may have resulted from contamination of urine specimens, electrolyte content of food not representative of the assayed aliquots or a balanced state not achieved and excretion actually exceeded intake (table VI).

The urinary sodium/potassium ratio averaged 1.26 while in the normal adult it averages 1.85 [48].

Males and female chimpanzees while restrained in a sitting position for 6 hours excreted an average of 4.0 and 2.0 mEq/kg/day of sodium, respectively [34]. The urine volume of the males was also nearly twice that of the females during this time. In the last 6 h. of the 24 h of restraint the males excreted 2.9 and the females 2.1 mEq/kg/24 h. Chloride excretion averaged 8.3 and 4.1 mEq/kg/24 h in the males and females respectively during the first 6 h increasing somewhat during the final period.

The reabsorbed fraction of sodium in a group of normal, immature chimpanzees [24] was found to average 99% (table III, Chimp. 1, 2 and 5). The sodium/potassium ratio averaged 1.12. In this same study elevation of the plasma concentration of PAH resulted in the excretion of nearly 5% of the filtered load of sodium (Chimp. 3 and 4). Excretion of the anions of the non-reabsorbable salt (PAH) requires the excretion of an equivalent amount of cations. Both sodium and potassium appeared to contribute in these two ex-

periments. In Chimp. 5, however, it appears that sodium was substituted for completely by potassium.

Marked retention of sodium was observed when chair-restrained chimpanzees were subjected to thermally-stressful temperatures (85°–90° F) with 50 % relative humidity for 20 h [33]. The animals were also deprived of food and water during this period. The sodium/potassium ratio fell from 0.74 to 0.06. A period of 48–72 h was required before values returned to normal. Urinary excretion of chloride also declined but did not follow qualitatively or quantitatively the direction of sodium. The loss of sodium and chloride through extrarenal (sweating) routes presumably resulted in this marked decrease in urinary sodium and chloride excretion.

Subjection of a chimpanzee to the stresses involved in an orbital flight resulted in a marked increase in urinary excretion of sodium chloride during and immediately thereafter [49]. When a number of animals were subsequently subjected to centrifuge tests which simulated the acceleration and deceleration stresses of space flight and re-entry similar results were observed. Sodium, and to a lesser extent, potassium and chloride excretion were increased. This study raises the question as to how space flight might alter kidney function in chimpanzee or man.

#### EXCRETION OF POTASSIUM

Under normal conditions only about 15 % of the filtered potassium is excreted in the urine attesting to the fact that it must be reabsorbed. The infusion of large amounts of potassium salts or the alkalinization of the urine resulting in the excretion of more potassium than was filtered indicates that it must also be secreted by the renal tubule. Active reabsorption of potassium is known to occur along the proximal tubule with little remaining in the fluid entering the distal convoluted tubule. In the distal convoluted segment most of the potassium is secreted, although some secretion has been found to occur in the collecting duct.

Since the filtered load of potassium is nearly completely reabsorbed in the proximal tubule its rate of excretion must be determined by those factors which directly affect its secretion in the distal portion of the nephron. Among those factors are: 1. the delivery of sodium to the distal secretory site effecting an exchange of potassium for sodium, 2. the alteration in the rate of hydrogen ion secretion, 3. the concentration of intercellular potassium, especially the renal tubule cells, 4. the increase in circulating levels of adrenocortical steroids, especially aldosterone and 5. the administration of mercurial diuretics.

HAMLIN [26] has reported the urinary excretion of 0.96 mEq/kg/day of

potassium by a group of chimpanzees on an intake of 0.82 mEq/kg/day. Normal adults excrete approximately 60 mEq/day or 0.86 mEq/kg/day (table VI).

The excreted fraction of filtered potassium was found to average 12.1 % at a time when only 94 % of the filtered sodium was being reabsorbed (table III, Chimp. 1 and 2). Administration of large quantities of PAH resulted in marked increases in potassium excretion. At a plasma PAH concentration of 100 mg % 68.3 % of the filtered potassium was excreted (table III), accompanying the excretion of the anions of the non-reabsorbable salt (PAH).

Potassium excretion remained unchanged in the presence of marked sodium retention in chimpanzees deprived of food and water and exposed to an environment of 85–95° F for 20 h [33]. During this period of negative potassium balance cellular potassium was presumably replaced by sodium.

The stresses of an actual orbital flight on the chimpanzee which resulted in a marked loss of urinary sodium, chloride and glucose during flight was followed by a marked retention of potassium [49].

#### RENAL TRANSPLANTATION

Sectioning and resuturing of the artery, vein and ureter implies complete surgical denervation of the transplanted kidney. For a number of years the belief that this procedure resulted in an increase in renal blood flow and urine flow prevailed. More recently investigators have conclusively shown that renal denervation does not affect glomerular filtration, renal blood flow or urine flow in non-traumatized and unanesthetized dog or man [50, 51]. The observed 'denervation hyperemia' and 'denervation diuresis' probably occurs following release from enhanced vasoconstrictor tone caused by the anesthesia and traumatic operative procedures. Convincing evidence that renal function is not significantly altered in man following sectioning of the renal vessels was provided by the successful transplantation of a kidney from one to the other of identical twins by MERRILL and his collaborators [52]. After a period of one year the creatinine clearance was 70 ml/min, the phenolsulfonphthalein excretion rate was 70 % in 2 h and the C<sub>in</sub> and CPAH approximated that of the right kidney which remained in the donor.

Once the effectiveness of immunosuppressive drugs was demonstrated, interest in homologous transplantation sharply increased. This led to the immediate need of more human donors. In an effort to circumvent this problem REEMTSMA performed, in 1963, the first chimpanzee-to-man renal heterograft [53, 54]. Both kidneys of a 41 kg male chimpanzee were transplanted in a



43-year old uremic male who had a preoperative serum creatinine of 10 mg % and a creatinine clearance of 3.7 ml/min. During the first 24-hour period following transplantation the Ccr rose to 78 ml/min and the urine output was 7,200 ml. The creatinine clearance reached its maximal rate of 104 ml/min by the 26th day.<sup>7</sup> During this same period the kidneys excreted approximately 340 mEq of sodium daily in a urine volume ranging from 3 to 8.5 l. Large losses of potassium were also observed. During the following three-week period the urine volume fell to 4 l and the excretion of sodium to approximately 150 mEq per 24 h. Transplantation of the kidneys of a 30 kg animal into a 23-year old woman whose creatinine clearance was 4 ml/min resulted in an immediate increase to 50 ml/min [54]. The 24-hour excretion of sodium and water also increased initially to 400 mEq and 18 l, respectively. During the following three-week period they gradually declined to approximately 25 to 100 mEq and 1800 ml, respectively. Six and one-half months later her renal function was described as normal.

An increase in renal function, characterized by a prompt diuresis and a significant increase in the creatinine clearance was observed in three of the four remaining heterotransplants performed by this group of investigators [54]. This prompted them to suggest that the heterografted kidney from chimpanzee to man may respond similarly to the homografted kidney from man to man.

When HUME transplanted the kidneys of a 130 lb chimpanzee into an extremely edematous patient they began functioning at once, excreting 54 l of urine in the next 24 h [53]. This marked diuresis, however, posed a real problem in maintaining fluid and electrolyte balance, especially potassium. It was suggested that the kidney of the chimpanzee, which is accustomed to handling a diet high in potassium may continue to excrete it at this rate despite the 'change of venue'.

STARZL [55] has reviewed all reported heterotransplants between man and animal, going back some 60 years when the kidneys of a goat and sheep were transplanted in two terminal uremic subjects. In comparing the more recent transplants of baboons and chimpanzees to man he concluded that there was a definite functional superiority in those subjects receiving the chimpanzee kidneys. The daily creatinine clearances were higher and relief of azotemia was more complete with less dependence upon steroid therapy.

7 Using the mean endogenous creatinine clearance of 2.36 ml/kg/min obtained in six chimpanzees the estimated clearance of this animal's kidneys would be 97 ml/minute. This value is remarkably close to the value (104 ml/min) obtained during the third post-transplant week when the patient was on a free intake of food and salt and there was no evidence of rejection.

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Author's address: Mr. JOHN A. GAGNON, Division of Medicine, Department of Metabolism, Walter Reed Army Institute of Research, Washington, DC 20012 (USA).



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## ENERGY METABOLISM OF THE CHIMPANZEE

H. E. DALE, M. D. SHANKLIN, H. D. JOHNSON and W. H. BROWN

University of Missouri, Columbia, MO

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### INTRODUCTION

This subject is distinguished by remarkable freedom of contradictory evidence and conflicting opinions. Only two studies have reported any substantial number of measurements, and the objectives and experimental conditions of each were so different that there is basis for neither confirmation nor contradiction. The fact that technically neither investigation fulfilled its stated objectives

must be weighed against the present paucity of such measurements and the probability or improbability of such measurements in the future.

BRAUN and BENEDICT [5] sought to measure basal metabolic rate for the purpose of interspecies comparisons and to identify the effects of age, sex, and environmental factors. But the fact of the chimpanzee – his prehensile hand, his inquisitive and sometimes volatile nature, and even his sense of humor – then as now precluded basal measurements in the usual sense. Of necessity the measurements were made under conditions conducive to sleep, a state acknowledged to be something less than basal. The findings of this investigation, however, present the best, the only, such information available.

DALE, SHANKLIN, JOHNSON and BROWN also sought to measure basal metabolic rate but in chimpanzees that were awake and unrestrained. The results presented make it apparent that the two things, basal state and the chimpanzee, have not been reconciled in the intervening years. Heat production and heat loss were measured simultaneously, not so much to demonstrate exact equivalence as to note temporal relationships; but production did exceed loss and the reason for the discrepancy is in large part a guess, not substantiated by measurement.

The present chapter will review only briefly the work by BRAUN and BENEDICT. It will be concerned principally with findings of the second study which are not readily accessible [7], although some information which is available elsewhere [6] will be repeated here as a matter of convenience.

#### PRIOR WORK

BRAUN and BENEDICT have reported what is still the most comprehensive study of energy metabolism in the chimpanzee. Working, for the most part, with the collection at the Yale Anthropoid Experiment Station at Orange Park, Florida, these investigators conducted a total of 212 experiments on 22 chimpanzees ranging in age from 2 months to 15 years, from 3 to 50 kg in body weight. An open circuit technique and chemical methods of gas analysis were employed. Measurements were made in the evening, and the subjects were at least 12 h post-absorptive; they were confined in a relatively small chamber but otherwise unrestrained. It was the opinion of the authors that the apes were sound asleep during most of the experiments.

The observations are the best approximation of the basal metabolic rate in this species. There is no basis for re-evaluation of this data; the interpretations of the authors, their conclusions, are as valid today as at the time of

publication. A brief summary of the results is perhaps an injustice, but not all readers may have access to the original.

Environmental temperature was somewhat at the discretion of the subjects who had access to shade in the summer, heated living quarters in the winter, and outdoor ambient at all times. Most measurements were made at a chamber temperature of 25 to 29° C; the authors conclude that the zone of thermal neutrality for the chimpanzee is quite wide, 20 to 29° C, provided there has been time for acclimation. Abrupt exposure to temperatures below 20° C of animals which have not been acclimated will cause a decided increase in metabolic rate.

Variability was one of the unusual features reported in this study. Individual variation of as much as 30% is reported, and only in part could this be related to known influences. Depth of sleep was suggested as a possible reason for the variation but acknowledged to be somewhat less than satisfactory. The paradox of a basal rate and this variation was not really resolved, but the authors suggest that measurements over a two week period will provide an average which can be used as a basis for comparison.

Concern for unifying principles in biology has led to expression of metabolic rate in units that minimize differences within and between species. The concept of a metabolic size, body weight in kilograms to the 0.73 [3] or 0.75 [10, 11] power, has been one result. Data for the chimpanzee presented by BRUHN and BENEDICT cover an extended weight and age range; fortunately they are sufficiently complete to permit computation to the liking of the reader. The authors prefer to discuss their findings in terms most applicable to man, kilograms of body weight to the  $2/3$  power or surface area. The average value, 980 calories per  $10^{2/3}$  kg, is approximately the same as that for man; the fact that this average value did not change consistently with weight or age is, of course, a striking difference.

The authors did not demonstrate a significant sex difference in the rate of energy metabolism; nor did they find consistent change with season of the year.

#### THE PRESENT INVESTIGATION A COMPARISON OF HEAT LOSS AND HEAT PRODUCTION

##### *Methods*

Measurements were made on 14 chimpanzees (*Pan troglodytes*) provided by the 6571st Aeromedical Research Laboratory. Body weight ranged from 11.3 to 27.2 kg, estimated age from 42 to 74 months. Seven females and seven males were studied; none, however, were sexually mature. More detailed vital statistics are included in tables I-III.

The observation period for any one animal was approximately 3 months in duration; 3 chimpanzees were on hand at any one time. The entire period of measurement extended from September 1963 to April 1965.

### *Feed and Care*

Insofar as possible the ration fed during the study was identical to that fed in the colony at Holloman Air Force Base. Breakfast was fruit: apple, orange, and banana; lunch a pabulum supplement; and dinner was Purina monkey pellets. Preparation of these materials and the amounts fed were in accordance with recommendations of the 6571st Aeromedical Research Laboratory [14]. During the 3 month period of study for each chimpanzee the average increase in body weight was 2.9 kg.

The chimpanzees were housed in individual cages measuring  $40 \times 30 \times 29$  in. Starting at 8:00 a.m. the chimpanzees, one at a time, were removed from these cages, placed in a transfer cage, and transported by heated automobile to the calorimeter, a distance of approximately 2,000 ft. The sequence of testing was rotated among the 3 subjects on hand; the test period for any one chimpanzee was 55 min long.

Upon completion of the test period each chimpanzee was returned to his individual cage and fed his allotment of fruit, the first meal of the day. After the fruit had been consumed, each chimpanzee was released into a large common cage,  $14 \times 15 \times 8\frac{1}{2}$  ft, for a play period; the first subject tested each day was in this common cage for approximately 5 h, the last for approximately 3 h. The pabulum supplement was given to the chimpanzees during this play period, usually  $1\frac{1}{2}$  h after completion of the last test. The interval between the fruit and the pabulum then was 1 to 4 h depending upon the sequence of the test.

The chimpanzees were returned to the individual cages after the play period; pellets were placed in the feeder and the subjects were left undisturbed for approximately 1 hour. At 4:45 p.m. remaining pellets, if any, were removed from the feeder, lights were turned off; and, under ordinary circumstances, the chimpanzees were left undisturbed until the start of testing on the following morning at 8:00 a.m.

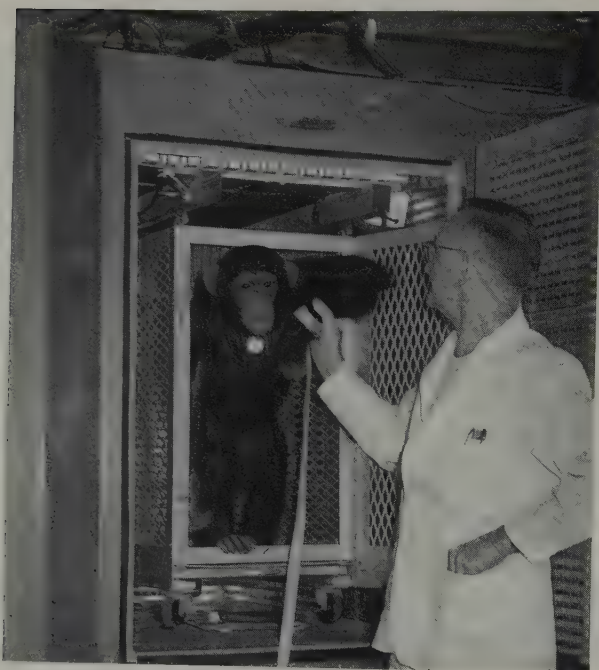
All cages were cleaned daily, and fresh drinking water was available at all times except during the actual test period. Ambient air temperature was  $75 \pm 2^\circ\text{F}$ ; no attempt was made to control humidity.

### *The Test*

Upon arrival at the calorimeter, the transfer cage was carried into an ante-room. The cage was opened, and the chimpanzee, guided by the fore-arm, walked from the cage to the chamber of the calorimeter (fig. 1), a distance of approximately 8 f. In the calorimeter the subject was confined in an expanded metal cage,  $35 \times 17 \times 30$  in. This cage was suspended in the chamber of the calorimeter approximately 3 in from the walls, the ceiling and floor.

The weight of the cage was 59.9 kg; its purpose was to prevent chimpanzee damage to the thermocouples lining the interior of the calorimeter. This cage was routinely kept in





*Fig. 1.* The chimpanzees, guided by the fore-arm, walked approximately eight feet to the chamber of the calorimeter. (Photograph by MILTON D. SHANKLIN.)

the calorimeter, it was removed only for cleaning. At the start of a test the temperature of the cage was that of the ventilating air, 75° F. The interior of the calorimeter was lighted with a one-watt fluorescent panel; soothing folk music, usually a cowboy ballad, was played over a speaker system to the more active subjects.

Within the confines of the cage in the calorimeter the chimpanzee was free to move about. The degree of activity during the test period was variable. During most tests most subjects apparently sat quietly on the floor and displayed minimal activity; occasionally, however, bursts of muscle activity were apparent. Accelerometers attached to the cage were used to gauge this activity until it became apparent that these supplied no information not obvious from inspection of the radiant heat loss trace and gas analysis records.

After the subject was confined in the cage and the door of the calorimeter closed, measurements were made for approximately one hour. The first 15 min of this hour were regarded as an equilibration period, and data collected during this time were discarded. The assumption was that heat exchange between the subject, the cage and the calorimeter would reach an equilibrium during this period and that the composition of the exhaust air would have reached a plateau.

When activity of the subject was sufficient to result in a 50% or larger increase in heat production or when urination or defecation occurred in the calorimeter, the results

were excluded from consideration. When activity was minimal, as gauged by uniformity of the measurements, data collected during a 40-minute test period were averaged and this mean value is presented as the measurement, calories per kilogram per hour, for the test period. Each of the indirect values is derived from approximately 100 determinations of oxygen and carbon dioxide content of the exhaust air; each of the direct values from approximately 533 determinations of each component of heat loss.

By visual inspection a 10-minute low period was delineated from each 40-minute test period. Data collected during this period were averaged and are presented as an estimate of the basal metabolic rate, i.e., heat production by a *resting*, post-absorptive subject in a thermally neutral environment. For the indirect system the value for any one low period represents the average of 25 determinations of oxygen and carbon dioxide in the exhaust air from the calorimeter; for the direct system each low value represents the average of 133 individual determinations of each of the 3 components of heat loss.

### The Calorimeter

The general arrangement of the thermoelectric calorimeter and the respiratory gas analysis system is diagrammed in figure 2. The two systems were actually housed in adjacent rooms; a gaseous event in the calorimeter, for example opening the door of the chamber, was detected 2 min later by the gas analysis system.

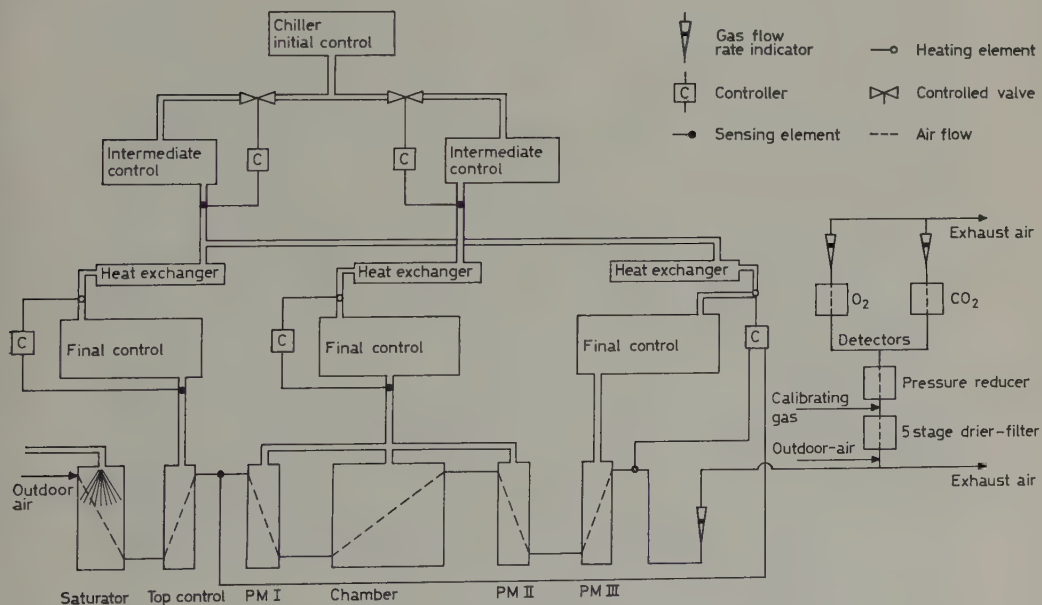


Fig. 2. Schematic diagram of the thermo-electric partitional calorimeter and the respiratory gas analysis system.

Factors affecting the composition of the calorimeter air have been identified by QUATTRONE [15] as 1.  $K_1$ : change due to introduction of ventilating air, 2.  $K_2$ : change due to introduction or removal by the subject in the chamber of the calorimeter, and 3.  $K_3P$ : change due to removal by the exhaust air stream. The interaction of these factors is defined by the equation:

$$dP/dt = K_1 + K_2 - K_3P$$

Conditions pertinent to this experiment were:

Volume of the calorimeter chamber: 991.2 l

Ambient temperature: 75° F

Ambient pressure: 745 mm Hg

Relative humidity: 50%

Ventilatory flow rate: 354 l/min

Using these data and  $K_2$  values equal to 1%, 10%, and 20% of oxygen, carbon dioxide, and water vapor in the ventilating air stream, integration of the equation revealed a consistent time course of gaseous composition: 90% of the total change occurred within 9 min, 99% of the change in 13 min.

### *Direct System*

Heat loss was measured with a thermoelectric calorimeter based upon one described by BENZINGER [1, 2] and similar to those used by others [8, 15]. The Missouri partitional calorimeter differs, however, in that it measures electrically all of the heat added to the air by the subject and, in addition, partitions the radiation fraction from the total sensible heat.

The walls of the calorimeter act as a constant temperature heat sink and the thermal gradient across the wall, proportional to the amount of heat flowing through the wall, is measured with 2 thermopiles: radiation and total sensible. The total sensible gradient layer lies next to the chamber wall and is covered by the radiation thermopile which consists of a series of thermojunctions serially connected in one plane. This layer is covered with a radiation absorbing layer of mylar over which is placed a radiation reflective aluminum tape covering alternate junctions so that the alternate reflection and absorption enables thermoelectric separation of radiation as a component of the total heat loss of the subject.

Insensible heat loss, vaporization from skin and lungs, was measured from the amount of water added to the ventilating air as it passed through the chamber. Air at room temperature (70–80° F) was saturated by spray and then chilled to 55° F, a temperature below the spray dew point temperature, to establish a constant chamber dew point. Subsequently, the air was heated to 75° F in a plate meter just ahead of the chamber, and was then passed into the chamber of the calorimeter where the subject added moisture. The exhaust was again chilled to 55° F in a final plate meter and the water added by the subject was condensed within it and measured electrically.

Output of the radiation thermopile was recorded with a Leeds and Northrup Speedomax G. Model S. 6000 series recorder; the outputs from the total sensible thermopile and from the plate meters used to measure latent heat were recorded with Leeds and

Northrup Speedomax H, Model S, series 60 recorders. Response time of each of these recorders was less than one second for full scale deflection. Information from the 3 recorders was integrated by a Leeds and Northrup 3-channel Data-Handling System which read each recorder at 4.5-second intervals.

Calibration data, periodically collected, show that the accuracy of the direct system was  $\pm 0.2523$  BTU per hour for the gradient layer (total sensible heat),  $\pm 0.050098$  BTU per hour for the radiant layer, and  $\pm 0.0002611$  pounds per hour for evaporation or insensible heat loss.

### *Indirect System*

Approximately 10% (30 l) of the air exhausted from the calorimeter was diverted through a respiratory gas analysis system<sup>1</sup>. This air was filtered and dried, the temperature adjusted to 122°F (maximal variation  $\pm 0.2^\circ\text{F}$ ) and pressure to 29.94 in of mercury (maximal variation of  $\pm 0.02$  in), conditions that were maintained during the process of analysis. This dry, heated air was divided into 2 sample streams for oxygen and carbon dioxide determination. Flow in each stream was directly proportional to the volume of the detector and inversely proportional to the response time of the detector; it was adjusted to secure simultaneous phasing of the signal output from each detector. Flow through the actual detector was between 1 and 2 l per minute. Oxygen analysis was based on measurements of magnetic susceptibility with a Pauling meter<sup>2</sup>. Carbon dioxide analysis was based on infrared absorption.

Initially detectors giving full-scale deflection with 1% change in gas composition were used; these were subsequently replaced with detectors showing full-scale deflection with 0.1% change in gas composition. When air of presumably constant composition (outdoor atmospheric) was passed through these detectors some variation of the recorded output was apparent. For oxygen the standard deviation of this variation was  $\pm 0.002\%$  and  $\pm 0.0007\%$ ; for carbon dioxide it was  $\pm 0.0014\%$  and  $\pm 0.0006\%$ .

The output of both the oxygen and carbon dioxide analyzers was adjusted to a zero reading while outside atmospheric air which had passed through the empty calorimeter was flowing through the analyzer. The analyzers with 1% range were adjusted to give full scale deflection for air containing 19.93% oxygen and 1.03% carbon dioxide by the use of a gas mixture of known composition (20.07% oxygen and 0.81% carbon dioxide). The analyzers with 0.1% range were adjusted to give full scale deflection for air containing 20.83% oxygen and 0.13% carbon dioxide using another gas mixture of known composition (20.874% oxygen and 0.078% carbon dioxide).

Heat production was calculated from oxygen consumption, the whole body respiratory quotient (R.Q.), and the usual caloric equivalents of oxygen [12]. Nitrogen excretion was not measured and no allowance was made for gasses involved in protein metabolism. Such a method of calculation yields a quantity of heat somewhat larger than if allowance were made for protein metabolism; the difference due to the fact that oxygen used in protein metabolism is generally assigned a caloric equivalent of 4.48

1 Assembled by General Measurements, Inc., Division of Precision Scientific, Garnerville, NY.

2 Beckman Instruments, Fullerton, CA.



while that used for the metabolism of fats and carbohydrate at a R. Q. of 0.84 a caloric equivalent of 4.85. The difference however is not large. If 4 mg of nitrogen are excreted per calory (twice BRODY's estimate of 2 mg of endogenous urinary nitrogen per calory), a 20 kg subject consuming 10.34 L of oxygen per hour would excrete 0.2 g of nitrogen per hour. Heat production calculated without allowance for protein metabolism would amount to 50.15 calories per hour; if the usual allowance were to be made for protein metabolism, i.e., 5.9 l oxygen per gram of nitrogen with a caloric equivalent of 4.48, total heat production would be 49.77 calories per hour. The difference, 0.38 calories per hour, is less than 1% of the total. It was assumed that such calculations would not alter significantly the results of the experiment.

### *Alcohol Tests*

Simultaneous performance of the two mechanisms, direct and indirect, was periodically evaluated by the combustion of ethanol in the chamber of the calorimeter. An alcohol lamp was weighed before and after ignition in the chamber of the calorimeter; the outputs of the 2 systems were compared with each other and with the heat of combustion estimated from the weight of alcohol consumed.

## RESULTS AND DISCUSSION

### *Calibration*

The combustion of ethanol served as a metabolic model to permit comparison of the direct and indirect calorimeters. In theory, any measured quantity of alcohol reacted with a definite amount of oxygen to produce predictable amounts of carbon dioxide, water vapor, and sensible heat. The techniques of indirect calorimetry estimated this heat from the amount of oxygen used in the combustion; direct calorimetry actually measured the heat.

A total of 66 tests with alcohol was conducted. The high correlation coefficient<sup>3</sup> between the direct and indirect measurements, 0.966, indicated that change in the rate of oxygen consumption was closely paralleled by change in the amount of heat measured with the direct calorimeter.

Not only did the 2 measurements change together but, in addition, the amount of heat measured with the 2 systems was approximately the same. The mean difference between heat production estimated from oxygen consumption and heat measured by the direct calorimeter, 0.863 calories<sup>4</sup> per hour, was not statistically significant ( $t = 1.838$ ). The observed difference was a relatively

3 This and all subsequent statistical procedures from SNEDECOR [16].

4 The calorie or kilocalorie is equal to 1,000 calories.

small fraction, 2.32 %, of heat loss; or, conversely, the amount of heat measured with the direct calorimeter was 97.73 % of that estimated from oxygen consumption.

The amount of heat calculated from the weight of alcohol which disappeared was also closely correlated with both the direct ( $r = 0.971$ ) and indirect ( $r = 0.965$ ) measurements. Again change in amount of alcohol was closely paralleled by change in oxygen utilization and change in heat production.

There was, however, an appreciable difference between heat calculated from the loss of alcohol and heat measured with either the direct or indirect systems; on the average the amount measured with the direct calorimeter was 88.2 % of this hypothetical quantity, the heat estimated from oxygen consumption 90.2 % of that which would have come from complete combustion of the alcohol. This discrepancy, while interesting, is not, however, really pertinent to the problem at hand which is the relationship between oxygen and heat and not the relationship between fuel and heat. The cause of the discrepancy is not known; vaporization and incomplete combustion of alcohol are, at least in part, responsible.

### *Metabolic Rate of the Chimpanzee*

All individual estimates of the basal metabolic rate for male chimpanzees available to the authors are plotted on figure 3, those for females on figure 4. Specifically these figures show the values obtained on sleeping subjects by BRUHN [4] and BRUHN and BENEDICT [5]; they show the individual low periods from the study under discussion. In all there is a total of 1,052 measurements on 39 subjects.

Tables I to III summarize the data for each subject by test period, i.e., whether the animal was tested promptly after he was awakened or whether there was an intervening period of several hours. Heat production during the low period, the best approximation of a basal rate, was used for the calculation of calories per unit of surface area ( $\text{kg}^{2/3}$ ) and per unit of metabolic size ( $\text{kg}^{3/4}$ ). In tables IV to VI the data is summarized by sex and then for all subjects; these tables also present the partitional heat loss and the comparison of heat production and heat loss.

### *The Basal Metabolic Rate*

The basal state identifies standard conditions for the subject. In part, feeding and environmental control, the state is at the discretion of the investigator;

in part the state requires cooperation, voluntary or inadvertent, of the subject. Management for the basal state in man, environmental temperature and time after eating, must be modified somewhat for other species; but although the details may not be entirely agreed upon, they can be identified and imposed on a subject. For the chimpanzee the appropriate conditions are apparently quite similar to those for man. BRUHN and BENEDICT report 20–29°C as a zone of thermoneutrality; in the second study all measurements were made at 24°C. For both investigations the subjects were at least 12 h post-absorptive.

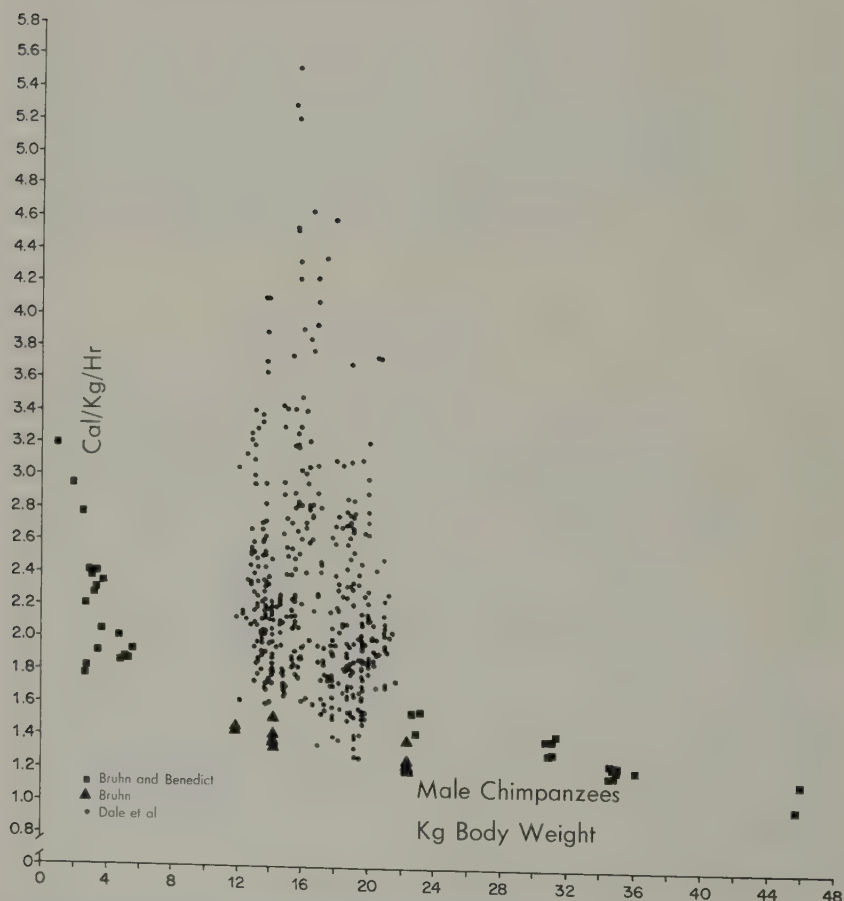


Fig. 3. Individual values for basal metabolic rate of male chimpanzees. Measurements were made on sleeping subjects by BRUHN and by BRUHN and BENEDICT, on awake and unrestrained subjects by DALE *et al.*

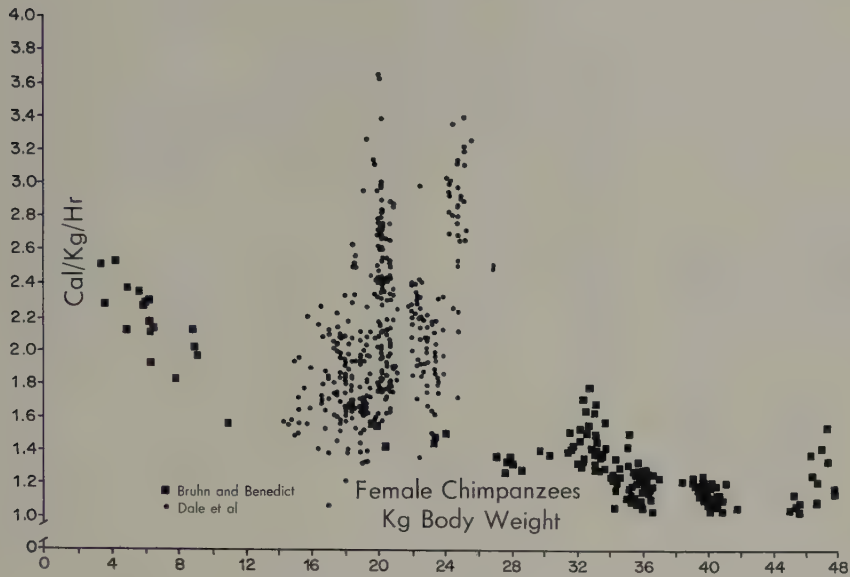


Fig. 4. Individual values for the basal metabolic rate of female chimpanzees.

Table I. Individual calorimetric data collected during first test period of the day, approximately 8:00–9:30 a.m.

Chimp Female	Age, months	Body weight initial $\bar{x}$ kg	Heat loss <sup>1</sup> cal/kg/h		Heat production <sup>1</sup>			
			Test period	Low period	Test period cal/kg/h	Low period, cal per		
						kg/h	24 h/kg <sup>3/4</sup>	24 h/kg <sup>3/5</sup>
154	46	20.6	2.148	1.959	2.803	2.776	143.01	184.75
155	48	20.4	2.593	2.473	2.719	2.617	134.64	173.59
156	50	24.1	2.039	1.900	2.232	2.110	110.67	143.99
207		18.4	1.895	1.660	2.069	1.887	95.32	122.09
208	61	25.3	2.676	2.311	2.995	2.806	151.58	198.72
148	53	21.2	1.913	1.832	2.185	2.015	103.95	134.17
187	57	17.2	1.759	1.375	2.041	1.759	88.06	110.79
$\bar{x}$	52.5	21.0	2.146	1.930	2.435	2.281	118.18	152.59
Male								
171	51	18.6	2.013	1.639	2.096	1.920	97.96	125.87
211	38	14.3	2.313	2.192	2.309	2.188	104.45	131.39
157	50	21.4	1.861	1.581	2.135	1.749	90.47	116.87
194	29	15.7	2.797	2.426	3.025	2.588	123.37	155.18



Table I. (Continued)

Chimp Female	Age, months initial	Body weight $\bar{x}$ kg	Heat loss <sup>1</sup> cal/kg/h		Heat production <sup>1</sup>			
			Test period	Low period	Test period cal/kg/h	Low period, cal per		
						kg/h	24 h/kg <sup>3/4</sup>	24 h/kg <sup>2/3</sup>
129	74	20.6	2.338	2.015	2.689	2.402	123.76	159.67
171(2)	59	22.3	1.733	1.400	2.045	1.905	99.86	129.50
199	39	17.1	2.200	1.934	2.466	2.174	106.52	134.36
218	43	17.9	3.048	2.357	3.813	2.874	142.01	180.97
$\bar{x}$	47.9	18.5	2.288	1.943	2.572	2.225	111.05	141.73
$\bar{x}$ all		19.7	2.222	1.937	2.508	2.251	114.38	146.80

1 Each value represents on the average the mean of 18 determinations.

Table II. Individual calorimetric data collected during the second test period of the day, approximately 9:30–11:00 a.m.

Chimp Female	Age, months initial	Body weight $\bar{x}$ kg	Heat loss <sup>1</sup> cal/kg/h		Heat production <sup>1</sup>			
			Test period	Low period	Test period cal/kg/h	Low period, cal per		
						kg/h	24 h/kg <sup>3/4</sup>	24 h/kg <sup>2/3</sup>
154	46	20.6	2.118	1.912	2.540	2.318	119.42	154.08
155	48	20.4	2.589	2.471	2.546	2.480	127.43	164.28
156	50	24.1	2.221	2.086	2.270	2.148	113.81	148.13
207		18.4	2.189	1.995	1.963	1.781	89.85	115.08
208	61	25.3	2.791	2.263	3.156	2.542	137.38	180.59
148	53	21.2	2.134	2.033	1.941	1.756	90.17	116.32
187	57	17.2	2.282	2.047	2.156	1.917	94.59	120.17
$\bar{x}$	52.5	21.0	2.332	2.115	2.367	2.135	110.38	142.66
Male								
171	51	18.6	2.495	2.198	2.128	1.895	96.24	123.07
211	38	14.3	2.509	2.317	2.293	2.172	103.86	130.72
157	50	21.4	1.879	1.626	1.992	1.681	87.88	112.03
194	29	15.7	3.288	2.989	3.129	2.621	124.77	156.79
129	74	20.6	3.153	2.772	3.226	2.682	138.03	178.00
171(2)	59	22.3	2.304	2.060	2.128	1.967	102.77	133.12
199	39	17.1	2.620	2.364	2.322	2.061	100.71	127.93
218	43	17.9	3.907	3.116	4.494	3.518	173.66	221.28
$\bar{x}$	47.9	18.5	2.769	2.430	2.714	2.325	115.98	147.87
$\bar{x}$ all		19.7	2.565	2.283	2.552	2.236	113.37	145.44

1 Each value represents on the average the mean of 19 determinations.

Table III. Individual calorimetric data collected during third test period of the day, approximately 11:00 a.m.–12:30 p.m.

Chimp Female	Age, months	Body weight initial $\bar{x}$ kg	Heat loss <sup>1</sup> cal/kg/h		Heat production <sup>1</sup>			
			Test period	Low period	Test period cal/kg/h	Low period, cal per		
						kg/h	24 h/kg <sup>3/4</sup>	24 h/kg <sup>2/3</sup>
154	46	20.6	1.934	1.715	2.304	2.077	108.44	137.87
155	48	20.4	2.357	2.193	2.448	2.310	118.84	153.26
156	50	24.1	2.224	2.087	2.187	2.092	110.48	143.99
207		18.4	2.010	1.838	1.910	1.667	84.01	107.60
208	61	25.3	2.753	2.085	3.116	2.471	133.43	174.90
148	53	21.2	2.020	1.902	1.957	1.755	90.70	117.03
187	57	17.2	2.040	1.766	1.991	1.723	87.39	111.45
$\bar{x}$	52.5	21.0	2.191	1.941	2.273	2.014	104.76	135.16
Male								
171	51	18.6	2.481	2.210	2.129	1.985	101.02	129.66
211	38	14.3	2.590	2.384	2.236	2.066	98.19	123.31
157	50	21.4	1.774	1.558	1.880	1.719	88.57	114.26
194	29	15.7	3.475	3.076	3.338	2.799	133.06	167.12
129	74	20.6	2.682	2.141	2.992	2.385	122.29	157.58
171	59	22.3	2.222	2.012	2.128	1.995	104.39	135.85
199	39	17.1	2.359	2.144	2.271	1.969	95.94	121.46
218	43	17.9	4.159	3.283	4.729	3.618	176.94	224.81
$\bar{x}$	47.9	18.5	2.718	2.351	2.713	2.317	115.05	146.76
$\bar{x}$ all			2.472	2.160	2.508	2.176	110.25	141.35

1 Each value represents on the average the mean of 18 determinations.

The basal state, however, is only partially a matter of management; the other aspect requires a pattern of behavior, physical and mental repose. This nirvana-like state is ordinarily achieved by voluntary cooperation of the subject; certainly without such cooperation it is only the occasional, somewhat accidental, measurement which can be classified properly as basal.

The intelligence of the chimpanzee suggests that, with proper training, measurements could be made in the basal state; such however have not been accomplished, or at least reported, at this time. Other than for man, the principal value of basal data has been for interspecies comparisons, and the measurements on sleeping chimpanzees by BRUHN and BENEDICT have been accepted as a close enough approximation for this purpose.

Table IV. Summary and analysis of calorimetric data for male chimpanzees

Run No. of Observ.	Direct (cal/kg/h)				Indirect		Comparison of direct and indirect			
	Rad.	Con.	Vap.	Total	R.Q.	cal/kg/h	Corr. D/I r	$\bar{x}$ dif.	S.E.	t
test										
1 146	0.643	0.759	0.894	2.295	0.86	2.573	0.879 <sup>2</sup>	-0.278	0.028	-9.984 <sup>2</sup>
2 149	0.726	0.939	1.137	2.802	0.83	2.775	0.897 <sup>2</sup>	0.027	0.035	0.761
3 134	0.727	0.932	1.074	2.733	0.83	2.756	0.918 <sup>2</sup>	-0.023	0.037	-0.610
$\bar{x}$	0.698	0.876	1.035	2.608	0.84	2.701	0.888 <sup>2</sup>	-0.092	0.020	-4.544 <sup>2</sup>
(S.E.)	±0.107	±0.276	±0.524	±0.782	±0.06	±0.915				
Low										
1 146	0.585	0.628	0.745	1.958	0.86	2.225	0.773 <sup>2</sup>	-0.267	0.028	-9.394 <sup>2</sup>
2 149	0.693	0.835	0.950	2.478	0.82	2.367	0.826 <sup>2</sup>	0.110	0.033	3.283 <sup>2</sup>
3 134	0.687	0.777	0.890	2.354	0.83	2.336	0.864 <sup>2</sup>	0.018	0.034	0.529
$\bar{x}$	0.654	0.747	0.861	2.262	0.84	2.309	0.810 <sup>2</sup>	-0.047	0.020	-2.350 <sup>1</sup>
(S.E.)	±0.114	±0.286	±0.407	±0.669	±0.07	±0.676				

Table V. Summary and analysis of calorimetric data for female chimpanzees

Run No. of observ.	Direct (cal/kg/h)				Indirect		Comparison of direct and indirect			
	Rad.	Con.	Vap.	Total	R.Q.	cal/kg/h	Corr. D/I r	$\bar{x}$ dif.	S.E.	t
test										
1 128	0.642	0.756	0.734	2.132	0.86	2.424	0.824 <sup>2</sup>	-0.292	0.024	-11.929 <sup>2</sup>
2 132	0.690	0.849	0.774	2.313	0.83	2.336	0.770 <sup>2</sup>	-0.022	0.029	- 0.766
3 138	0.679	0.826	0.681	2.186	0.83	2.268	0.796 <sup>2</sup>	-0.082	0.028	- 2.916 <sup>2</sup>
$\bar{x}$	0.671	0.811	0.729	2.211	0.84	2.341	0.771 <sup>2</sup>	-0.130	0.017	- 7.726 <sup>2</sup>
(S.E.)	$\pm 0.059$	$\pm 0.134$	$\pm 0.335$	$\pm 0.454$	$\pm 0.08$	$\pm 0.518$				
Low										
1 128	0.601	0.634	0.682	1.917	0.85	2.272	0.738 <sup>2</sup>	-0.355	0.032	-11.235 <sup>2</sup>
2 132	0.664	0.743	0.700	2.107	0.83	2.111	0.608 <sup>2</sup>	-0.004	0.032	- 0.139
3 138	0.642	0.701	0.593	1.937	0.83	2.008	0.650 <sup>2</sup>	-0.071	0.030	- 2.392 <sup>1</sup>
$\bar{x}$	0.636	0.693	0.657	1.987	0.84	2.127	0.632 <sup>2</sup>	-0.140	0.019	- 7.240 <sup>2</sup>
(S.E.)	$\pm 0.070$	$\pm 0.163$	$\pm 0.302$	$\pm 0.424$	$\pm 0.08$	$\pm 0.472$				

Table VI. Summary and analysis of calorimetric data for all chimpanzees

Run No. of observ.	Direct (cal/kg/h)				Indirect		Comparison of direct and indirect			
	Rad.	Con.	Vap.	Total	R.Q.	cal/kg/h	Corr. D/I r	$\bar{x}$ dif.	S.E.	t
test										
1 274	0.642	0.757	0.824	2.219	0.86	2.506	0.862 <sup>2</sup>	-0.285	0.019	-15.214 <sup>2</sup>
2 281	0.708	0.896	0.969	2.572	0.83	2.565	0.880 <sup>2</sup>	0.004	0.023	0.159
3 272	0.702	0.879	0.879	2.456	0.83	2.512	0.899 <sup>2</sup>	-0.053	0.023	- 2.270 <sup>1</sup>
$\bar{x}$	0.684	0.844	0.891	2.417	0.84	2.528	0.869 <sup>2</sup>	-0.110	0.013	- 8.300 <sup>2</sup>
(S.E.)	±0.088	±0.221	±0.469	±0.675	±0.07	±0.769				
Low										
1 274	0.592	0.636	0.715	1.939	0.86	2.248	0.753 <sup>2</sup>	-0.308	0.021	-14.482 <sup>2</sup>
2 281	0.679	0.793	0.831	2.303	0.83	2.243	0.785 <sup>2</sup>	0.056	0.023	2.407 <sup>1</sup>
3 272	0.664	0.742	0.739	2.142	0.83	2.173	0.825 <sup>2</sup>	-0.027	0.023	- 1.209
$\bar{x}$	0.645	0.724	0.762	2.130	0.84	2.222	0.763 <sup>2</sup>	-0.092	0.014	- 6.544 <sup>2</sup>
(S.E.)	±0.095	±0.239	±0.373	±0.581	±0.08	±0.593				
1 Indicates probability of 0.05.										
2 Indicates probability of 0.01.										

In the present study the subjects were awake, they were post-absorptive, and maintained in a thermally neutral environment. Some of the individual values probably do represent the fortunate accident where the subject was relaxed and immobile; however most of the tests were distorted by muscle activity of varying degree. But the spectrum is continuous; it is impossible to draw a line which separates basal values from those which are elevated by activity. The data are presented not as estimates of the basal metabolic rate in the usual sense, but rather to show the range of values obtained in unrestrained chimpanzees managed so that basality is possible. The average value, 2.221 cal/kg/h or 1445 cal/10 kg  $\frac{2}{3}$ /24 h contrasts with the comparable figure presented by BRUHN and BENEDICT, 980 cal/10 kg  $\frac{2}{3}$ /24 h, reported to be relatively constant for both males and females of all ages and weights.

The correlation between cal/kg/h and body weight was significant,  $r = -0.156$ , but it was low because of the individual variation and because of the limited weight range under observation.

#### *Comparison of Heat Production and Heat Loss*

Data in the preceeding tables enable three conclusions relative to this subject:

1. both heat production and heat loss change during the period of measure-

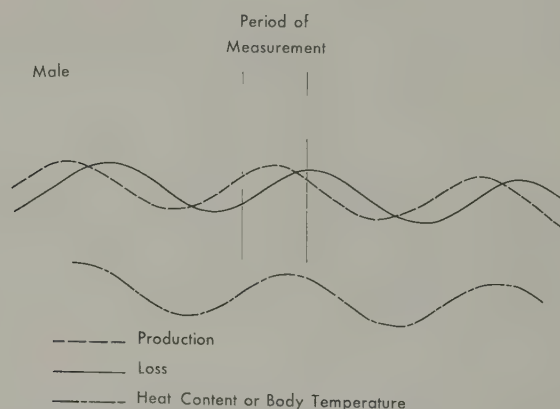


ment, 2. the two processes are significantly and positively correlated, and 3. heat production, calculated from oxygen consumption, is significantly larger than heat loss.

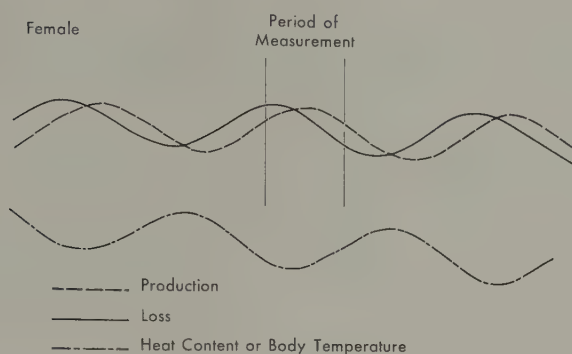
Heat production and heat loss in the animal are ultimately equivalent. This assumption is self-evident; none other will account for a body temperature that is constant over a period of weeks or years. For the short interval, however, minutes or hours, the situation is somewhat different; body temperature is not constant but rather changes diurnally and with a variety of activities. Specifically for the chimpanzee diurnal fluctuations of  $1.5^{\circ}\text{F}$  have been reported with skin temperature perhaps 4 times as variable [13]. For these variations in body temperature two explanations relevant to energy metabolism merit consideration.

The most logical assumption is that change in body temperature does reflect change in heat content and hence a difference between production and loss. If this is the case then the demonstrated facts would suggest relationships between the two processes like those schematically presented in figure 5 for males and figure 6 for females. Specifically in both of these figures heat production is larger than heat loss during the period of measurement, the two processes are significantly and positively correlated, and both production and loss do change.

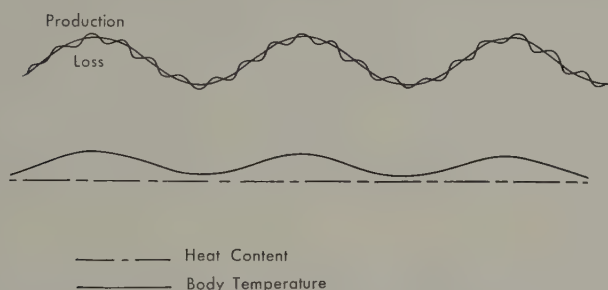
The alternative explanation is that heat content of the body is constant for the short interval in a manner somewhat analogous to the long interval; in



*Fig. 5.* A possible relationship between heat production, heat loss, body temperature, and heat content of the body for male chimpanzees. The diagram is consistent with the observed facts in that production is significantly larger than loss, both processes change during the period of measurement, and there is significant correlation between the two processes.



*Fig. 6.* Same as figure 5 but for female chimpanzees. In contrast to the males, heat production of the females declined during the hours of measurement.



*Fig. 7.* If heat production and heat loss are equal to each other during the period of measurement, the relationship between heat content, body temperature, and the two processes is approximately that above. It must then be assumed that the usual caloric equivalents of oxygen are incorrect under the conditions of this investigation.

this case change in body temperature would be entirely a matter of heat distribution. The later might involve expansion or contraction of the core at the expense of the shell or local fluctuations because of circulatory or metabolic alterations. This interpretation would suggest a relationship between heat production and heat loss like that shown in figure 7. This diagram is consistent with the observed facts in that production and loss do change during the period of measurement and in that the two processes are significantly and positively correlated. Not consistent with the observed facts is that production and loss are equal in the diagram; in the chimpanzee production was greater than loss. Heat production, however, is derived from measured oxygen consumption

and the caloric equivalents of oxygen [12]. To accept this explanation for the observations in the chimpanzee is to say in essence that the caloric equivalents of oxygen are measurably incorrect for this species under the circumstances described in the preceeding paragraphs.

The dilemma, such as it is, could be resolved. If heat content of the body does change then measurements over a 24-hour period would reveal that the observed period of a positive heat balance was offset by a comparable period of negative heat balance. The other solution would entail studies on well trained subjects where heat content of the body might be calculated from measurements of rectal and skin temperatures; change in heat content in turn related to the difference between production and loss.

In the meantime the most plausible assumptions are that heat content and rectal temperature are directly related and that there is in consequence a measurable difference between heat production and heat loss. The alternative explanation of a constant heat content necessitates unlikely circulatory or metab-

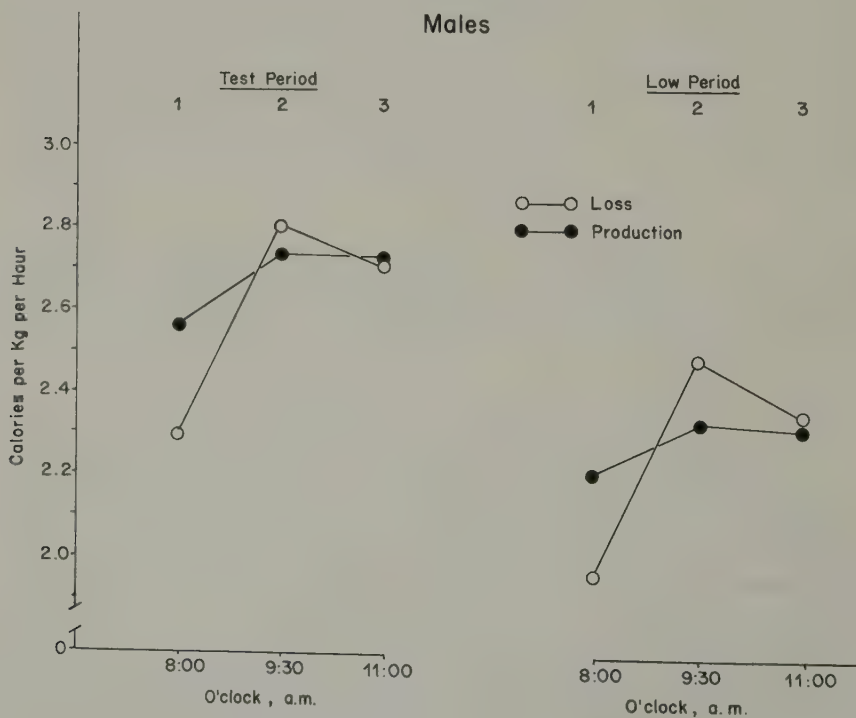


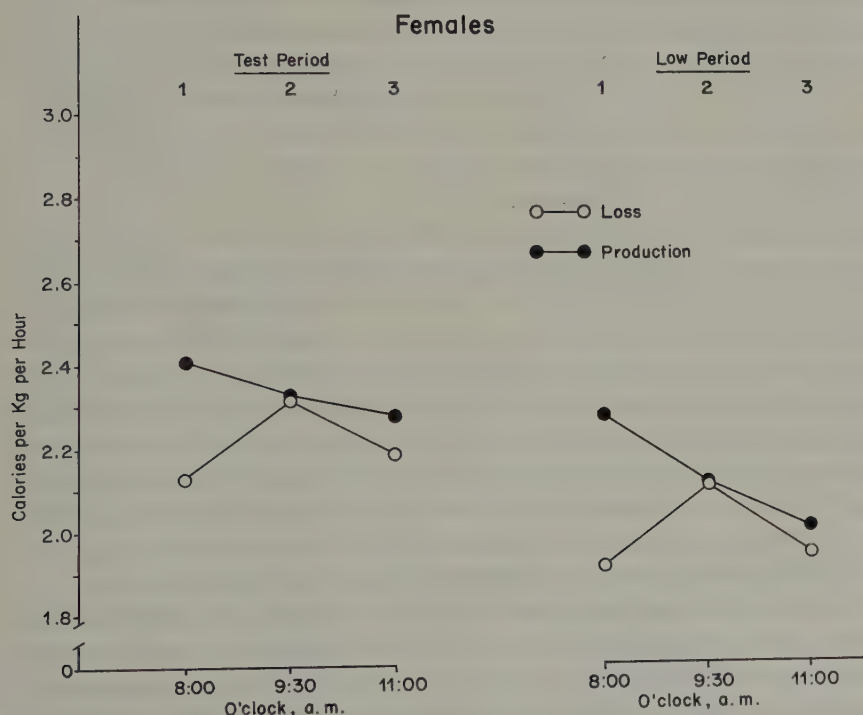
Fig.8. Observed values for heat production and heat loss during

olic acrobatics as well as revised caloric equivalents of oxygen which might not reconcile with physical chemistry; the explanation must be rejected as less probable.

In conclusion it is noted that the data presented above are evidence that as LAVOISIER intimated, there is no such thing as a *vital source* of animal heat. Indeed the problem observed in the chimpanzee is quite the opposite; production exceeded loss. The opportunity, however, is obvious, and so the last (ludicrous) resort to explain the observed difference between production and loss must be the *vital sink*.

### Sex Differences

Figures 5 and 6 are schematic; the observed mean values are shown in figure 8. The single most striking feature is that heat production of the females declined as the morning advanced while that of the males was higher at mid- and late



test period and low period for male (left) and female (above) chimpanzees.



morning (test periods 2 and 3) than it was in early morning (test period 1). It is tempting to speculate on endocrine differences in the circadian cycle of energy metabolism, and increasing oxygen consumption after 12 h of food deprivation may indeed be due to the action of testosterone. Such a response may be a matter of energy substrates, enzyme activation, or membrane permeability in peripheral tissues, but an alternative explanation should also be considered. Namely that even in these sexually immature subjects the psychological response of the male to a 12-hour fast was quite different from that of the female.

Undocumented observations were that females were less active and less aggressive than males; the difference enough so that, without exception, personnel working with the chimpanzees preferred females to males. During the hours of testing the females were more likely to remain placid and accept the wait and the fast with equanimity; males, on the other hand, were more apt to express dissatisfaction with the whole procedure, and invariably in a way that increased muscle activity. Tantrums, locking fingers and toes in the mesh of the cage and jumping or shaking, were more often a problem with the males. Belligerent behavior is perhaps a harsh judgement; suffice it to say that the personality of the males was almost always distinguished by features that involved muscle contraction and increased energy metabolism. Such behavior of course may have a hormonally mediated molecular explanation at the level of the central nervous system; but whether the mediation is peripheral or central, the sex difference is quite real.

The data summarized in figure 8 are consistent with the reported rise in rectal temperature of the chimpanzee during the morning hours [13]. Although the relationship is not constant, i.e., the rate of change of production and loss are different, there is none-the-less an overall positive heat balance during the hours of testing. This fact, in itself, was rather predictable; however, that it was accomplished during a time of declining metabolic rate in the females and increasing metabolic rate in the males was totally unexpected and suggests a fundamental difference between the two sexes. The observations reaffirm dramatically that in a thermally neutral environment body temperature, and the diurnal fluctuations in body temperature, depend upon an ability to regulate heat loss so that it has the proper relationship to heat production.

In addition to the features already considered, there are significant differences in the magnitude of energy metabolism between the sexes. Heat production of the males was 8.5 % higher than that of the females during the low period ( $t = 4.46$ ), 15.3 % higher during the test period ( $t = 6.9$ ). Some part of this is due to body size since the males averaged 18.5 kg and the females

21.0 kg. All of the data fitted to linear regression equations show that approximately 20% of the observed differences in metabolic rate could be so explained. The rest of the difference between the sexes could not be ascribed to body size, and it too was significant during both the test periods ( $t = 5.46$ ) and the low periods ( $t = 3.66$ ).

### *Partition of Heat Loss*

Heat is lost from the animal body by physical processes, radiation, convection and conduction, and the evaporation of water. The relative importance of these processes depends largely on environmental temperature.

In an ambient surround having a weighted mean temperature of 75° F nude man loses approximately 70 % of body heat by radiation, about 10 % by convection and conduction, and 15 % by evaporation of water. Between 80 and 90° F man begins to sweat and as a consequence can shift the burden of heat loss to vaporization. Close to this critical temperature, between 85 and 90° F, convection and conduction account for perhaps 20 % of heat loss, vaporization and radiation for approximately 40 % each [9]. At higher environmental temperatures radiation and convection lose their effectiveness and all body heat is lost by the evaporation of water.

The partitional heat loss for the chimpanzee at an environmental temperature of 75° F was roughly comparable to that for man close to or slightly above the critical temperature, 85 to 90° F. At a temperature of 75° F the chimpanzee lost about the same amount of heat by each of the 3 processes involved, with the loss by radiation slightly lower and less variable than the loss by convection and vaporization.

The hair of the chimpanzee, rather coarse and sparse, is apparently a fairly effective barrier to radiation while permitting enough circulation of air to remove appreciable amounts of heat by vaporization and convection. An alternative explanation would be that radiation was less effective in the chimpanzee than in man because of a lower skin temperature; this, however, seems unlikely in view of the large loss by convection, a process which would also lose its effectiveness at low skin temperatures.

The relatively high proportion of heat loss by vaporization suggests the activity of sweat glands and that perhaps the critical temperature for sweating in the chimpanzee (assuming that he does sweat) is somewhat lower than it is for man. This, however, is a matter of conjecture, although it does suggest the potential value of partitional calorimetry at different environmental temperatures.

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Authors' address: Dr. HOMER E. DALE, Dr. MILTON D. SHANKLIN, Dr. HAROLD D. JOHNSON and Dr. WILLIAM H. BROWN, University of Missouri, Columbia, MO (USA).

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# TEMPERATURE STUDIES ON THE CHIMPANZEE

W. E. WARD and E. R. ARCHIBALD

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## INTRODUCTION

The remarkably constant body temperature of homeotherms is the result of the interplay between heat production and heat loss. Changes in ambient temperature provide the stimulus for homeostatic adjustments and bring into play mechanisms which represent the end-product of evolutionary adaptation.

In the zone of thermal neutrality, the resting homeotherm lives at his basal metabolic rate [1]. At higher and lower temperatures (within a narrow range) homeotherms maintain a constancy of core temperature by physiological means (panting and sweating) and by certain behavior patterns (resting in the shade during the heat of the day and nocturnal activity).

The natural habitat of the chimpanzee (*Pan*) is hot and humid. Like man, the chimpanzee appears to be a late-comer in the geologic scheme of things [2]; like man, the chimpanzee is sociable, intelligent, may pant if the ambient temperature reaches a critical point, but usually maintains a rectal temperature similar to man's (98.6°F) [3].

The range of chimpanzee skin and body core temperatures under certain conditions of the environment forms the basis of this chapter.



## THE TEMPERATURE-HUMIDITY TEST SITUATION

ARCHIBALD *et al.* [4] investigated the tolerances of young restrained chimpanzees to extremes of environmental temperature. Although an attempt was made by PATTISHALL and KRICKOVIC [5] to collate this material, the majority of work remains unpublished. Therefore, some detail will be given to test conditions.

The object of the temperature test program was to define optimum, minimum and maximum temperatures and relative humidities for young, restrained chimpanzees. WARD [6] had conducted a study which showed conclusively that it was feasible to train young (2–5 years) chimpanzees to accept a restraint garment (fig. 1) and to sit quietly in isolation for periods of time up to twenty-four hours. The subjects for the temperature tests were healthy restraint-acclimated chimpanzees, ranging in weight from 12 to 25 kg. (Acclimated is

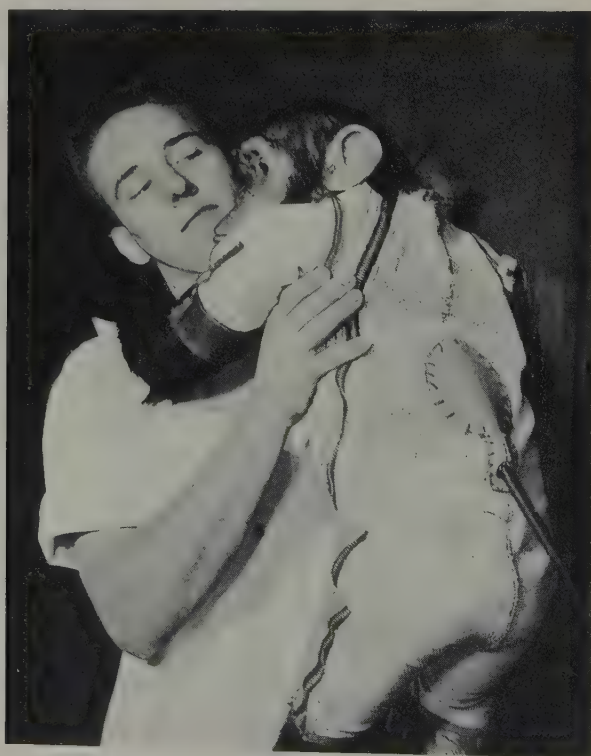


Fig. 1. Young chimpanzee in restraint.

defined as a functional compensation over a period of days in response to restraint.) The tests were programmed for 20 h duration and the subjects received no food or water during this time. The tests were terminated if the subject's rectal temperature reached 105°F.

Initially a number of thermocouples were utilized on the Belding points, but the subjects lost little time in removing the majority. Finally, point 4 (mid-thigh) alone was selected. Because of limited data [5] no conclusions could be drawn regarding the relationship between various aspects of areas of the skin. Rectal temperature was obtained by inserting an esophageal-rectal probe into the rectum approximately 9 in. The resistance was measured by a bridge circuit of a Yellow Springs Telethermometer. Details concerning the test chamber and experimental procedure are fully described elsewhere [4].

Results of the first three tests (based primarily on observations of rectal temperature) indicated that an environmental temperature of 80°F and 50% relative humidity represented a 'comfort zone' or zone of thermal neutrality. Subsequent control tests were conducted under these conditions.

## RESULTS

The environmental data and results obtained from 8 twenty-hour control tests on 5 animals (4 females and 1 male) are shown in figure 2. Although there was some minor deviation in environmental temperature and humidity, dry bulb temperature was maintained at a deviation of  $\pm 5^\circ\text{F}$ , and relative humidity at  $\pm 5\%$  of programmed values. Oxygen and carbon dioxide readings were well within physiologically normal limits at all times (All data were read at 15-minute intervals during the 20-hour periods). Plots are based on means and average deviations from all control tests. The tests usually began at 10 a.m.; hence, the rectal temperature curve is a close approximation of the diurnal cycle in the chimpanzee. The high point occurs about noon at 100°F; the low point about midnight at 98°F. The results indicate that the mean skin temperature of the young chimpanzee is about 3 to 4°F below rectal temperature, and that the skin temperature (at least at the medial thigh) is about four times more variable than the rectal temperature. Mean values of rectal and skin temperatures taken at 15-minute intervals during the 20-hour tests are shown in table I.

We must emphasize that only five different animals were used in the control series, and that four of these were females. Therefore, mean values may not be truly representative for young chimpanzees as a population. However it

was felt that these data would furnish a quantitative basis for judging the significance of changes in the values observed when chimpanzees were exposed to severe environmental stressors.

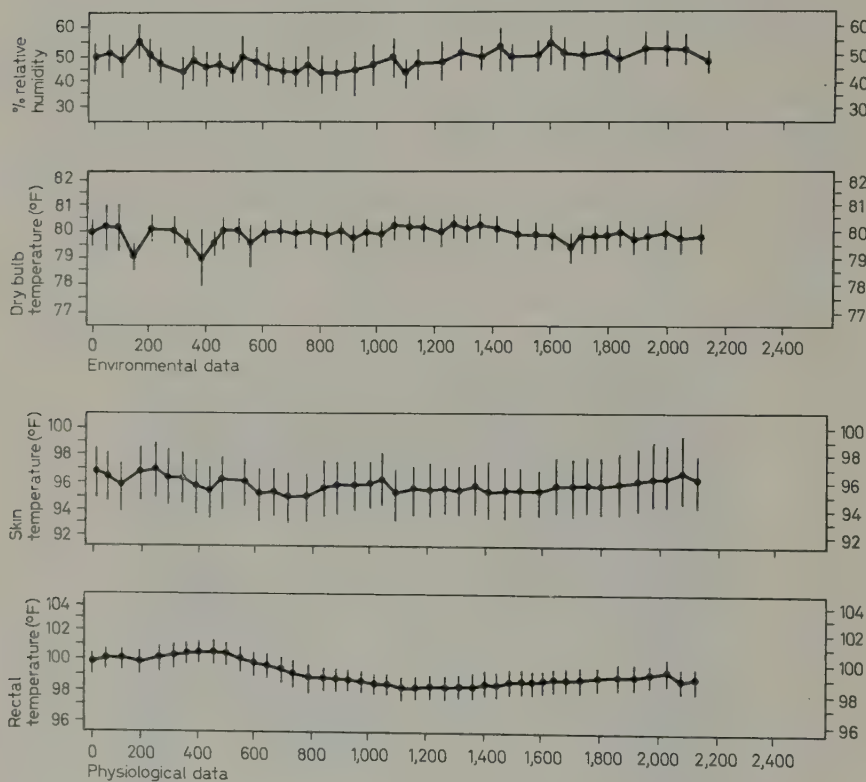


Fig. 2. Temperature-humidity control tests. Means and averages of environmental and physiological data from eight 20-hour tests. Test subjects were young (2-5 years) restraint-acclimated chimpanzees (four females and one male).

Examination of body weight pre- and post-test under the above environmental conditions revealed that body weight loss during the tests exceeded 5 % of original weight. ADOLPH [7] indicated that a loss of 5 % body weight in man results in serious dehydration. This finding prompted a series of tests at the same environmental temperature and humidity, but the subject was free to move about in a cage and had access to food and water. The restraint suit was

modified to protect the monitoring sensors (fig. 1). Results from 6 twenty-hour tests under these 'no restraint' conditions are presented in table II.

The data tend to confirm that an ambient temperature of 80° F and 50% relative humidity represents a comfort zone for the chimpanzee. Indeed, body weight loss of 5% in the chimpanzee may not be as significant as a similar weight loss in man. A comparison of restraint and no-restraint studies at 80° F and 50% relative humidity is shown in figure 3.

Tolerance studies at higher temperatures are summarized in table III and figure 4.

*Table I.* Chimpanzee temperature tolerance studies (80° F and 50% relative humidity)  
Rectal temperature (° F)

Mean	SD <sup>1</sup>	Range	N <sup>2</sup>
98.9	1.0	96.8–101.2	616
Skin temperature (° F)			
Mean	SD	Range	N
95.3	4.5	90.7–100.0	562

1 Standard deviation

2 Number of observations

*Table II.* No-restraint tests at 80° F – 50% relative humidity  
Body weight loss (% of initial weight)

Mean	SD <sup>1</sup>	Range	N <sup>2</sup>
1.57	0.85	0.90–2.80	4
Rectal temperature (° F)			
Mean	SD	Range	N <sup>3</sup>
98.6	1.78	95–101	345

1 Standard deviation

2 Number of animals

3 Number of observations



Table III. Chimpanzee temperature tolerance studies

Environmental conditions	Test duration – hours		N <sup>1</sup>
	Mean	Range	
85° F – 50% RH	14.2	2–20	6
90° F – 50% RH	14.8	5–20	5
100° F – 50% RH	6.4	2.2–13.7	7

1 Number of tests

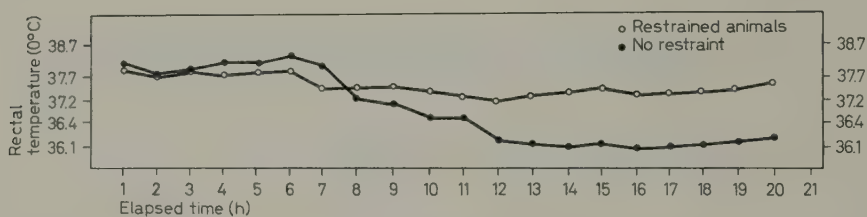


Fig. 3. Comparison of rectal temperatures of restrained chimpanzees and non-restrained chimpanzees. The values are based on mean temperatures. Number of tests in each situation is four.

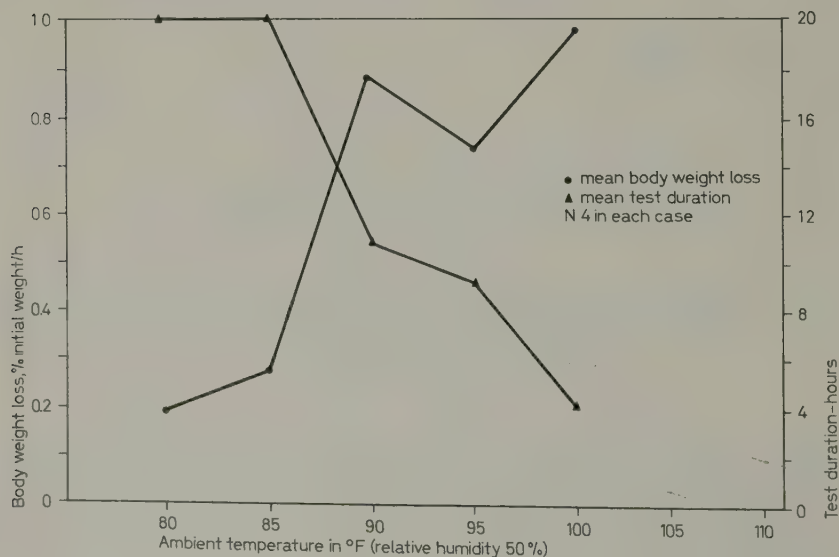


Fig. 4. Comparison of environmental temperature to body weight loss in the chimpanzee and duration of test. Based on four tests at each set of environmental conditions.

At an environmental temperature of 85°F, subjects maintained rectal temperatures of 101°–103°F, but exhibited marked dehydration (8.5% of body weight). The threshold for a 20-hour duration appears at 85°F (fig. 3); mean test duration is only 4 h at 100°F ambient.

#### SUMMARY

Two of the objectives of this test program were accomplished. The third, that of establishing minimum temperature tolerances as well as experimentation with various humidities, awaits further research. The results of our study indicate that rectal temperature of the chimpanzee reaches a high point (100°F) about noon. The average skin temperature in young chimpanzees is 3 to 4°F below rectal temperature. Skin temperature is about four times more variable than rectal temperature. The average skin temperature tends to parallel rectal temperature, but the diurnal rhythm is not as apparent.

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Authors' addresses: Dr. W.E. WARD, DFLS, USAF Academy, Colorado, CO 80840 (USA); Dr. E.R. ARCHIBALD, 427 Benton Blvd., Kansas City, MO 64124 (USA).

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## THE SENSE OF TASTE OF CHIMPANZEES AND OTHER PRIMATES

H. KALMUS

Galton Laboratory, University College London

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### INTRODUCTION

The sensations and sense organs of the chimpanzee and of the other primates are of particular interest, because 1. they allow the closest available comparisons with their known human equivalents and also 2. because these animals can provide the material for experiments, which we cannot perform on people. In addition 3. search for an equivalent of the human taster polymorphism for PTC in anthropoids might shed some light on an evolutionary aspect of anthropogenesis and on the antiquity and stability of a gene equilibrium in the anthropoids. In what follows only items (1) and (3) will be considered after a discussion of the available methods.

## METHODS

The ideas which one can have concerning the quality of the sensations of non-humans will always be somewhat uncertain and the confidence which one has in the interpretation of quantitative results, for instance in threshold determinations, should never be too great. On the other hand, certain types of overt behaviour – be it facial expression [DARWIN, 1872] or the concomitants of acceptance and rejection – are so similar to those of man and in particular infant – that it would be churlish not to interpret them in terms of sensations similar to our own; and threshold methods, by frequently resulting in values very similar to those obtained in man by means of ‘exact subjectivism’ [v. TSCHERMAK, 1932], must also surely inspire some confidence.

Electrophysiological methods might be expected to locate the sensors on the tongue for specific sapid substances, which in man produce the modal sensations of bitter, sweet, sour or salty; but in fact it has been known for a long time that even on the human tongue most areas (papillae) can mediate all these tastes, though different areas to different degrees. This makes the interpretation of results on primate tongues rather hazardous.

We are thus more or less confined to behavioural methods, which are all based on one or the other form of acceptance, rejection, preference or discrimination. Most of these overt reactions can be greatly influenced by previous experiences and by motivation [WEISSKRANTZ and COWEY, 1961, 1963, for chimpanzees], KUMAR *et al.* [1968, for monkeys], and this will have to be taken into account later on in this chapter; it should command great caution in interpreting differences of behaviour simply as the result of differences in taste-threshold. This point has not always been sufficiently considered in the past.

*Observation*

The animal is offered some specified food or drink and its overt motor responses to this are interpreted as acceptance, in the case of sweet substances for example, or rejection in the case of bitter substances; in both situations it is then assumed that the concentration of the sapid substance is above threshold. As pointed out by PATTON and RUCH [1944] responses of monkeys and chimpanzees to bitter food are particularly variable and difficult to quantify. The balance between the unpleasantness of the food (or drink) and the motivating factors for its acceptance, like hunger, thirst, or the experi-



menters' behaviour, vary not only from day to day, but even within an experimental session. In addition, WEISSKRANTZ and COWEY [1963] have shown that rhesus monkeys (*Macaca mulatta*) can 'get to like' certain foods, e.g. black currant juice or chocolate malted milk, which they at first had rejected with the appearance of strong disgust. KLÜVER [ref. FISHER, 1967] has repeatedly observed that rhesus monkeys liked and ate quinine powder. The author also has on several occasions been puzzled by similar occurrences, not only in monkeys and children, but even when experimenting with organisms as different as honey bees. Other factors which can greatly strengthen the motivation of an animal for food acceptance are the preference and the example of other animals. While it would be desirable to taste test every ape separately and in isolation, this is often not practicable, because many apes and other primates – especially when young – are used to act in groups and refuse to co-operate when separated from their mates. In the experience of the author young chimpanzees or gorillas will fight for a beaker given to one of them and hastily gulp solutions, which they would not otherwise accept. Similarly female patas monkeys, which have been chased away from some food by the much larger male, will stealthily creep back to it and eagerly devour it, when he is looking away, although the food may be so bitter, that later on the females may spit it out again.

### *Conditional Reflexes*

While most observational methods rely on the immediate reactions of the experimental animals to the qualities of the food, methods making use of conditioned reflexes also depend on previous experiences, that is on learning. The usual procedure of using the stimulus as a signal for reward or punishment is not particularly suitable for taste experiments on primates, though it should in theory succeed in determining the true sensory capacity of the animals. On the other hand it proved easy [unpublished] to associate – in the chimpanzees' minds – striking colours with a bitter taste; they rejected for instance cubes of sugar cane, which had been soaked in a bright yellow and intensely bitter solution of picric acid after a single experience. One young chimpanzee even threw a tantrum at the sight of such yellow cubes a day after his first taste of them. The speed of obtaining such conditioned reactions [JARVIK, 1953, 1956] which has been called 'one trial learning' [THORPE, 1966] is in striking contrast to the tedious and unreliable methods obtaining when colour and taste are not intimately connected with the food object, as for in-

stance on KLÜVER boards [HARLOW, 1951], where an animal may need several hundred trials before a reasonable criterion for colour discrimination is demonstrable.

### *Discrimination*

Discrimination methods, though successful in the study of visual sensations in primates, are difficult to apply to taste investigations, because it is difficult to make award or punishment dependent on quantitative discrimination between food samples or solutions.

### *Preference*

These are the most promising methods for taste threshold determinations in animals, though as PATTON and RUCH [1944] have pointed out the threshold values thus obtained may be somewhat higher than those obtained by discrimination or conditioned reflex methods. Preferences, like conditioning methods, do of course hinge on the faculty of discrimination, but in preference tests the motivation for discrimination is not artificially associated with the stimulus (e.g. an electric shock or food rewards) but is provided by the stimulus object itself. Typically the experimental animal is presented with two solutions, water and bitter (or sweet). If the animal in the absence of all non-gustatory cues, like position, temperature, odour etc. consistently prefers water (or the sweet solution), we conclude that it must be able to distinguish between the paired offerings. By progressively reducing the concentration of the sapid substance a point is reached, where equal volumes of water and the solution are drunk, and this concentration is called the preference threshold. A difficulty of this method is that it is impossible to deduce the significance of differential consumption from one volume pair alone; this can be overcome by presenting the animals with three or four pairs of liquids in randomized and changing positions. It should be pointed out that a substance which may be repellent at high concentrations may in fact be attractive at low concentrations – as for instance acids or salts would be to most people [ENGEL, 1928]. Therefore rejection may not simply vanish when we decrease the concentration of the sapid solution in a preference test, but may actually change into preference before disappearing at yet lower concentrations [BUTLER-THOMAS, 1961] in such a situation positive as well as negative preference indicates discrimination but two different ‘thresholds’ will obviously

be inferred. Whether for any particular substance a concentration exists, at which acceptance and rejection are so finely balanced that they consistently cancel each other out has to be experimentally determined.

Preference at any particular concentration may be measured by various expressions for instance

$$\frac{\text{volume of sapid solution} \times 100}{\text{volume of sapid solution} + \text{volume of water (= control)}}$$

In the case of a 'distasteful' substance one may distinguish between a 'threshold of acceptance', lying somewhere in a zone of equivalence when about equal amounts of water and solution are drunk, and a 'threshold of rejection' in a zone of rejection, where only small amounts of liquid – those necessary for sampling by the animal – are consumed. Between the two zones a range of concentrations can be characterized as a 'zone of partial rejection' (fig. 1). Rejection and acceptance thresholds for quinine in man, chimpanzee, monkey (*Macaca mulatta*) and laboratory rats are shown in figure 2. From these and similar values one may conclude that the quinine thresholds for man, chimpanzee and rhesus monkey are of the same order of magnitude, but that the thresholds of the rats are much lower.

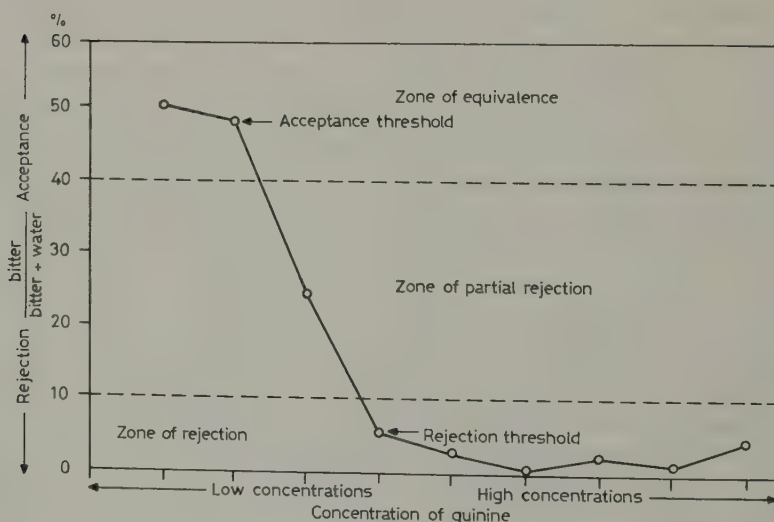


Fig. 1. Schematic preference threshold curve for a bitter substance [after PATTON and RUCH, 1944].

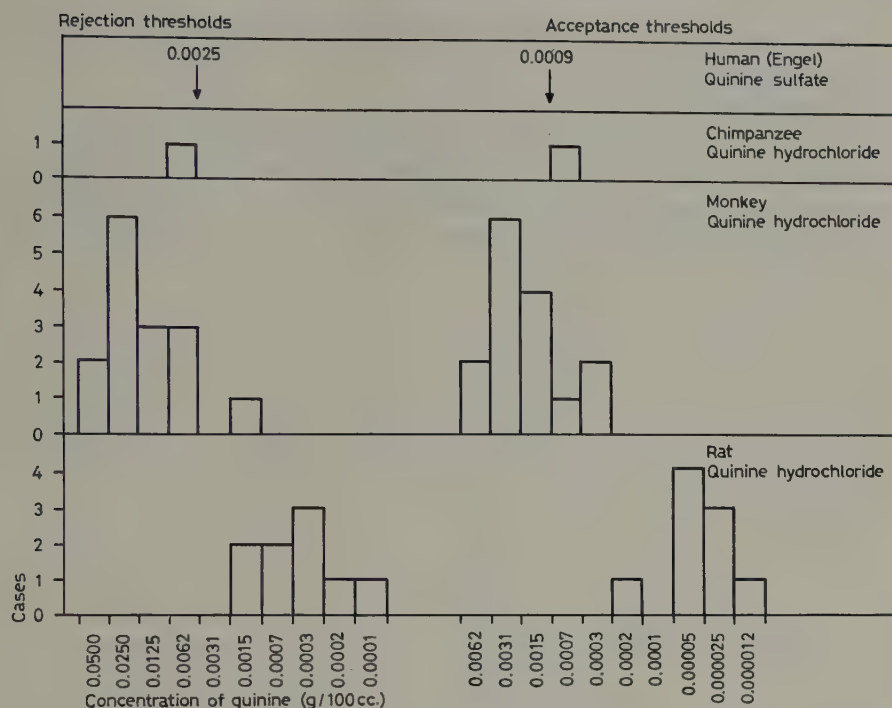


Fig. 2. Acceptance and rejection thresholds for quinine [from PATTON and RUCH, 1944].

### *The Taster Polymorphism for NC = S Compounds*

The possibility, that the human taste polymorphism for NC = S compounds, for instance PTC (phenylthiourea) which was discovered by FOX [1931] and genetically elucidated by SNYDER [1931] and BLAKESLEE [1932], might also exist in chimpanzees and other apes, first occurred to either FISHER, FORD or HUXLEY [1939] during the International Congress of Genetics at Edinburgh, just before the outbreak of world war II. These authors then proceeded to test a number of chimpanzees, orang-utans, gorillas and gibbons in the Zoological Gardens of Edinburgh, London and Whipsnade by offering them three solutions of PTC in 2 % sucrose, containing 6.25, 50 and 400 parts per million respectively. Human 'tasters' would generally find the first of these solutions perceptibly bitter, but not necessarily unpleasant, if the sugar was desired; the second solution would be to most tasters unpleasantly bitter



and the third decidedly so. Non-tasters might notice some slight bitterness at the strongest level.

Some of the apes accepted the strongest solutions and were accordingly classified as 'non-tasters', while those classified as 'tasters' showed reluctance or aversion sometimes to the weak, and always to the medium solution. On these animals the strong solution was also used for confirmation, whenever possible. Using these criteria 27 chimpanzees, 3 oranges, 2 gorillas and 4 gibbons were classified. The results are given in table I.

Table I. PTC tasters (T) and non-tasters (NT) according to FISHER, FORD and HUXLEY [1939]

	T	NT
Chimpanzees male	9	4
female	11	3
Orang-utan male	1	1
female	1	—
Gorilla male	2	—
Gibbon ( <i>H. concolor</i> )	2	—
( <i>H. lar, lar</i> )	—	1
( <i>H. lar, agilis</i> )	—	1

A young female chimpanzee, the daughter of two 'non-taster' parents in the Regent's Park collection, was also a 'non-taster' — as she would be expected to be if tasting was dominantly inherited as in humans — and was left out of the table.

From this evidence the authors concluded that a taste dimorphism, similar to the one described in man, occurs in at least 2 species of man-like apes and they remark that even the percentage of non-tasters among the chimpanzees (about 26 %) closely corresponds to the percentage 'regularly' found in man, namely 25–30 %. (At that time it was not generally known that many non-Caucasian populations show in fact a much lower percentage of non-tasters.) They further point out that there must have existed conditions of stable equilibrium, to keep the gene ratios the same over the million or more generations, which have elapsed since the separation of anthropoid and hominid stocks.

The observations and conclusions of the paper by FISHER, FORD and HUXLEY have been widely accepted and quoted, but though their observations — as far as they go — can be readily duplicated and have in fact been extended it

remains doubtful whether they can be interpreted in the way described above. Thus NISSEN [1956] found – in confirmation – that ‘some chimpanzees will drink a suspension of Nembutal (a NC = S compound) in fruit juice, whereas most animals refuse to accept this very bitter concoction’. However NISSEN also points out that those animals which accept even the higher concentrations of PTC do so not because they are insensitive to the bitterness, but because they apparently enjoy the taste. In view of similar observations quoted on page 131 of this paper and in accordance with the author’s experiences with chimpanzees and other primates it would seem that one can safely consider neither acceptance nor rejection as unequivocal criteria for taste thresholds.

CHIARELLI [1959] testing a further 81 primates (12 chimpanzees) in the Zoological Gardens of Italy and roughly following the procedure of FISHER, FORD and HUXLEY, offered his subjects biscuits, either soaked in a 2.5–3 % sucrose solution (control) or in the same sucrose solution containing also 400 ppm PTC. Like FISHER *et al.* he judged the taster status of his subjects by their acceptance or refusal as well as by their facial expression, and by such actions as throwing away the morsel, spitting or retching.

In a later publication [1963] CHIARELLI supplemented his Italian data by test results from primates in other European Zoological Gardens. The criterion for taster status in this additional material was however derived from judging the subjects’ reactions to ‘PTC powder sprinkled on a slice of fruit (apple)’ and not as in the Italian material to ‘biscuits soaked in sucrose solution containing 400 ppm PTC’. In spite of this change in method fairly consistent results were obtained with the chimpanzees.

Table II summarizes those results, giving overall a ‘non-taster frequency’ in chimpanzees of about 21.1 %.

CHIARELLI also tested 8 chimpanzees with FALCONER’s [1946] method using ascending as well as randomized concentrations on each individual. Both methods gave very similar results, which are summarized in figure 3.

Table II. Taster status of chimpanzees

Author	PTC presented	T	NT	Total
FISHER <i>et al.</i> [1939]	graded solutions	20	7 (25.9%)	27
CHIARELLI [1959]	biscuits soaked in 400 ppm	10	2 (16.7%)	12
CHIARELLI [1963]	powder on apple slice	71	18 (20.2%)	89
		101	27 (21.1%)	128

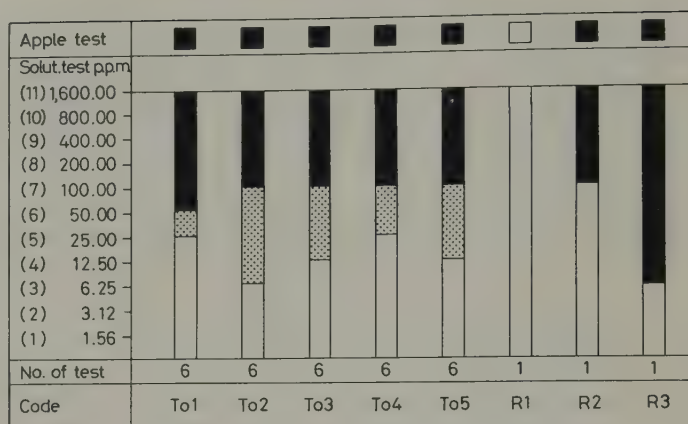


Fig. 3. Thresholds for PTC in 8 chimpanzees. The dotted zones indicate individual variation [from CHIARELLI, 1963].

This is taken to show that one of the chimpanzees was a non-taster.

Altogether CHIARELLI tested 712 primates ranging from prosimian to hominoidean. From the detailed – though limited – results, which are shown in figure 4, he felt able to draw the following conclusions. Among the *Platyrrhina* individuals of the genera *Ateles* and *Lagothrix* were non-tasters – according to the criteria described above – while *Callithrix* and *Leontocebus* individuals were tasters. The frequency of tasters in the genus *Cebus* was extremely low, while it was very high in the genus *Saimiri*. In the *Catarrhina* differences in tasting between the genera *Macaca*, *Papio*, *Theropithecus*, *Cercocebus* and *Cercopithecus* were very slight. Taster frequency in the genus *Colobus* was very similar to that of the other African monkeys (the cercopithecinae).

Among the anthropoids the gibbons had a taster frequency of about 50 %; orangs 5 %; chimpanzees and gorillas, like people were predominantly tasters.

My own studies as yet [unpublished] were like CHIARELLI's conducted in several Zoological Gardens of Europe, Nigeria and the United States, mostly before the latter's publications. Though I can confirm many of CHIARELLI's findings, I came to much more tentative conclusions. In fact I encountered so many difficulties with the various testing methods that I could not collect sufficient convincing data on the unique groups of chimpanzee families of the Yerkes Laboratories then in Orange Park, Fla. Nevertheless some observations and a few tentative conclusions might be reported here.

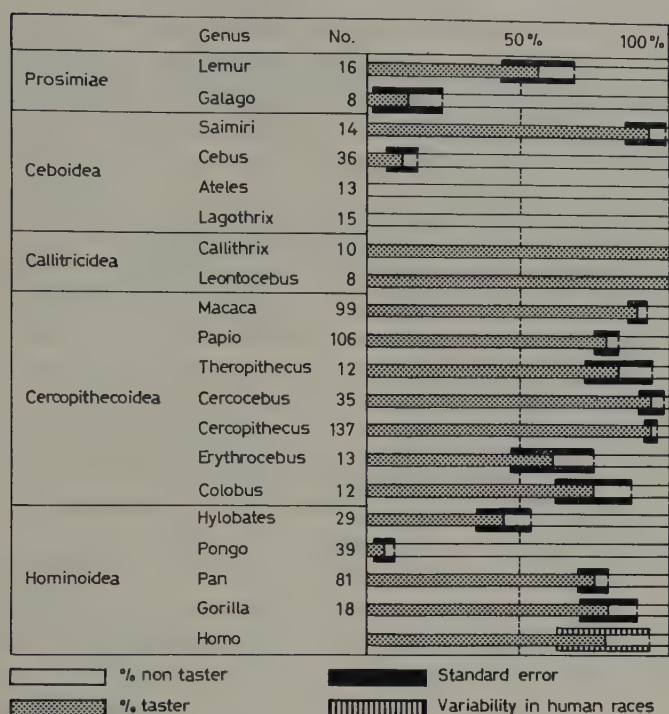


Fig. 4. 'Tasters' and 'nontasters' among primates. The chimpanzees include the 27 tested by FISHER *et al.* [1939]. The human values tested by the method of HARRIS and KALMUS [1949] [after CHIARELLI, 1963].

A valid comparison of PTC-thresholds in anthropoids and man would require the use of a comparable method. It is however not practicable to extend the method of HARRIS' and KALMUS [1949] to apes. So that simpler methods, which have proved inadequate in man must be resorted to.

The reactions of chimpanzees, oranges and gorillas to drink or food differ in many details. Solutions of varying bitterness as well as bits of fruit or spoonfuls of ice cream were as a rule accepted by most young adults of all three species. Some 'old' individuals however could not be enticed to co-operate, while baby chimpanzees could be tested by feeding them milk, made bitter by adding various substances through a teat.

The responses of the chimpanzees to bitterness were much more lively and varied than those of the two other species. They pulled faces, spat, refused to accept the sample, walked away or even furiously banged the experi-



mental set up. Gorillas were much more placid, 'inscrutably' just accepting or not accepting consecutive samples. Orangs were even quieter; sometimes they spat out a sample of banana or ice cream and then took it up in their mouth again while at other times they moved the food into the extended lower lip and after a while back into the mouth. It was often very difficult to decide whether an animal had accepted or rejected a particular sample.

The interactions between animals sharing the same cage were also very different, according to species. Many of the animals were so used to each other's company, that they refused to co-operate when separated. When tested in a group, the chimpanzees grew very excited and snatched drinking vessels or food morsels from each other, the dominant animal usually being victorious and the other complaining vociferously. The gorillas were less openly competitive but also tried forcibly to get hold of the samples. On several occasions one orang of a pair gently stroked the throat of his submissive companion, who then disgorged whatever he had swallowed and let the other eat it, without much commotion.

These and similar observations made it often very difficult to arrive at consistent and general criteria for acceptance or refusal. And while taste thresholds could be fairly confidently ascertained in many anthropoid individuals, it was rarely possible to determine the taster status of all members in a family group. Thus while I can state that my results are on the whole not inconsistent with the conclusion of my predecessors, that there exists a PTC-taste polymorphism in chimpanzees, similar to that in man, I do not consider this to be conclusively proven. Genetical and evolutionary speculations based on such tentative material must be regarded as premature.

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## THE SPINAL CORD (SPINAL MEDULLA) OF THE CHIMPANZEE<sup>1</sup>

C. R. NOBACK and SONYA K. SIMENAUER

Department of Anatomy, Columbia University  
New York, NY

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### GROSS ANATOMY

The gross anatomy of the spinal cord and the roots of the spinal nerves of the chimpanzee has been described by VIRCHOW [1888] and SERGI [1920, 1920–21]. A photograph of the *in situ* spinal cord within the vertebral canal is included in SERGI's accounts.

The spinal cord was 305 mm long and 26 grams in weight in a formalin-fixed female chimpanzee of 11,800 grams in weight and of 900 mm in length [SERGI, 1920–21]. The brain of this animal weighed 473 g. In a general way, the spinal cord of the chimpanzee is similar to the spinal cord of man with

<sup>1</sup> Unless specifically noted, the descriptions in this account are often based on observations made in other primates, especially man and the rhesus monkey. This is done because of the paucity of data on the spinal cord of the chimpanzee. It is assumed that common findings in such diverse species as man, rhesus monkey and cat are probably present in the chimpanzee.

the conus terminalis (medullaris) located at lumbar vertebral level 2 and with the filum terminale attached at sacral vertebral level 2. SERGI's specimen had 8 cervical segments, 13 thoracic segments, 4 lumbar segments, 5 sacral segments and a coccygeal complex; the eighth spinal cord segment was located at cervical vertebral 8 segment, the twentieth spinal cord segment (T 12) at the eighteenth vertebral level (T 11) and the twenty-fifth spinal cord level (L 4) at the twentieth vertebral level (T 13). SERGI includes such data as 1. the length of each root from its emergence at the cord to its intervertebral foramen, 2. the cross-sectional areas and volumes of the white matter and gray matter of each spinal segment, 3. ratios and indices of these areas and volumes, and 4. comparison of these data with that obtained from the spinal cord of man. The absolute values of many of these data are greater in man than in the chimpanzee.

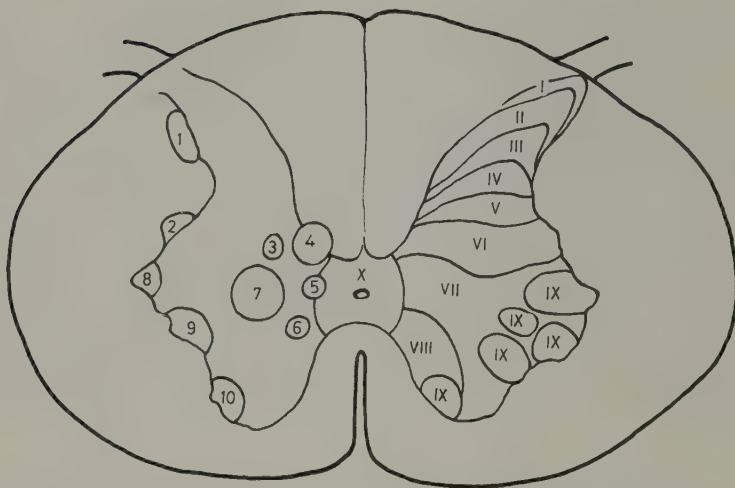
In summary, the descriptions and the data of the gross anatomy, topology and topography of the spinal cord of the primates including the chimpanzee, but with the exception of that of man and the rhesus monkey, are sparse.

#### CYTOARCHITECTURAL ORGANIZATION OF THE GRAY MATTER OF THE SPINAL CORD

The gray matter of the spinal cord has been parcellated into two cytoarchitecturally defined patterns: 1. schema of nuclei (nuclear columns, cell columns), and 2. schema of lamellae. These schemata are based upon morphological criteria observed on microscopic sections prepared by the Nissl method, a technique which primarily stains the cell bodies of neurons.

*Schema of nuclei* (fig. 1). This schema was based originally upon observations of the spinal cord of man [JACOBSON, 1908]. The nuclei in the chimpanzee are described by SERGI [1924a, 1924b, 1924c, 1926-27] with photographs [SERGI 1926-27]. The posteromarginal nucleus, substantia gelatinosa and nucleus proprius are nuclei of the posterior horn; these nuclei are present in all segments of the spinal cord. The thoracic (dorsal or Clarke's) nucleus, located in the medial base of the posterior horn, is present in cervical 8 through lumbar 2 levels. The lateral cervical nucleus, located in the lateral funiculus just lateral to the middle of the posterior horn, is present in the lower medulla and cervical levels 1 and 2. In the intermediate gray zone between the posterior horn and the anterior horn is the intermediomedial nucleus (present at all segmental levels), intermediolateral nucleus (present





*Fig. 1.* Schematic section through the eighth cervical segment of the chimpanzee's spinal cord (adapted from SERGI, 1920). The laminae of Rexed are indicated in Roman numerals (I through X) on the right half of the figure. Several nuclei are represented in Arabic numerals on the left side of the figure: 1 lateral cervical nucleus; 2 reticular nucleus; 3 posterior commissural nucleus; 4 thoracic (Clarke's) nucleus; 5 intermediomedial nucleus; 6 anterior commissural nucleus; 7 central cervical nucleus; 8 intermediolateral nucleus; 9 nucleus of the spinal accessory nucleus; and 10 phrenic nucleus. See text for explanations.

from cervical 8 through lumbar 2 levels), posterior commissural nucleus (not well differentiated at thoracic levels), anterior commissural nucleus, central cervical nucleus (present from C 1 through C 4 levels) and the reticular nucleus. The cell bodies of the preganglionic sympathetic neurons are located in the intermediolateral nucleus, while the cell bodies of the preganglionic parasympathetic neurons are scattered within the intermediate gray zone and anterior horn of sacral 2 through 4 levels.

The nuclei of the ventral horn have been subdivided into the medial group, lateral group and central group. The medial group is composed of the ventromedial nucleus, present at all spinal levels with possible exception of lumbar 5 and sacral 1, and the dorsomedial nucleus, present at all thoracic and upper lumbar levels. The lateral group is present in cervical enlargement and in the lumbar enlargement. This lateral group is often subdivided into a ventrolateral nucleus, dorsolateral nucleus and a retrodorsal nucleus. The central group includes the phrenic nucleus, present at midcervical levels, and the central nucleus, present in the lumbar enlargement. The nucleus of the spinal

accessory nerve is located in the anterior horn in the upper six cervical levels.

The precise muscle groups innervated by the anterior horn nuclei have not been experimentally established in any primate (see Output from the Spinal Cord for further comments). The nuclei do not necessarily form continuous longitudinal columns of cell bodies [SPRAGUE, 1951]. In general, the anterior horn is composed of root neurons and interneurons. The root neurons are the alpha motor neurons, which innervate the voluntary muscles, and the gamma motor neurons, which innervate the intrafusal muscles of the neuromuscular spindles. The interneurons are the intrasegmental neurons, intersegmental neurons and commissural neurons, which form the intrinsic circuits of the spinal cord. The neurons of the medial group innervate the axial musculature (back, intercostal and abdominal muscles). The neurons of the lateral group innervate the muscles of the extremities. The Renshaw neurons are interneurons with their cell bodies located in the gray matter near the site of emergence of the ventral roots [ROMANES, 1964] or scattered among the alpha neurons [SCHEIBEL and SCHEIBEL, 1966] or in the ventral portions of lamina VII [WILLIS and WILLIS, 1966]. The controversial aspects of identifying Renshaw 'Golgi type II' cells and gamma motor neurons are discussed by TESTA [1964]. No Golgi type 11 cells could be identified within the anterior horn by TESTA [1964] in the cat.

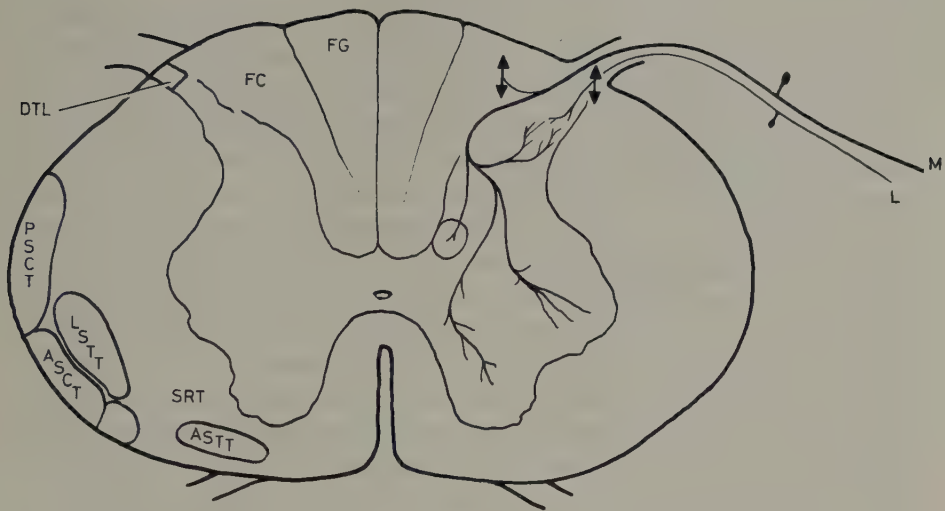
*Schema of lamina* (fig. 1). The cytoarchitectural lamellar pattern is visualized on thick Nissl stained sections [REXED, 1952]. This schema was first described in the gray matter of the spinal cord of the cat [REXED, 1952, 1954]; it has been utilized by several investigators in reporting experimental data in several primates. Because SERGI's photographs [1926-27] are from thin sections, the 'Rexed' laminae are not revealed in his illustrations. The intimate structure of the spinal cord is similar in all mammals [REXED, 1964]. On this basis it may be assumed that the chimpanzee's spinal cord has the same basic pattern as in other primates and cat [NOBACK and SHRIVER, unpublished]. There are ten cytoarchitecturally defined laminae extending longitudinally within the gray matter of the spinal cord (fig. 1). Some laminae are equivalent to the nuclei noted above. All laminae, except lamina VI, are present at all levels of the spinal cord. Lamina VI is present only in the upper cervical segments, cervical (brachial) enlargement and lumbosacral enlargement. Lamina I is the equivalent of the posteromarginal nucleus. Lamina II is the equivalent of the substantia gelatinosa. Laminae III and IV are the equivalent of the nucleus proprius. SZENTAGOTHAÏ [1964] states that the substantia gelatinosa is the

equivalent of laminae II and III). Laminae V and VI are located in the neck and base, respectively, of the posterior horn. In the rhesus monkey, laminae II through VI extend to the midline and are contiguous with the same laminae of the contralateral side in the lower spinal segments including some thoracic segments. Lamina VII is restricted to the intermediate gray zone except in the cervical enlargement and the lumbosacral enlargement. In the enlargements, lamina VII extends anteriorly to subdivide lamina IX. The thoracic nucleus of Clarke, intermediomedial nucleus, intermediolateral nucleus, anterior commissural nucleus, posterior commissural nucleus and central cervical nucleus are located within lamina VII. Lamina VIII is located in the dorso-medial aspect of the ventral horn except in the cervical enlargement and the lumbosacral enlargement where it is limited to the medial aspect of the ventral horn; its neurons are commissural neurons whose axons project through the anterior commissure to the contralateral side. Lamina IX is composed of the motor neurons of the anterior horn. Lamina X is located in the gray matter surrounding the central canal.

#### COURSE AND TERMINATION OF THE DORSAL ROOT FIBERS WITHIN THE SPINAL CORD

Experimental evidence indicates that the course and termination of the dorsal root fibers within the spinal cord are essentially similar in the rhesus monkey [FERRARO and BERRARA, 1935; WALKER and WEAVER, 1942; SHRIVER, STEIN and CARPENTER, 1968; CARPENTER, STEIN and SHRIVER, 1968] and in the cat [SZENTAGOTHAÏ, 1964; SPRAGUE and HA, 1964; RALSTON, 1965; STERLING and KUYPERS, 1967]. The distribution pattern of the dorsal root fibers in the chimpanzee, which have not been analyzed, is assumed to be similar to the basic pattern demonstrated in these two other mammals (fig. 2).

The primary afferent fibers of the dorsal roots, after passing through the posterolateral sulcus, segregate into a lateral bundle of unmyelinated to lightly myelinated fibers and a medial bundle of heavily myelinated fibers. The lateral bundle of thin fibers (fig. 2) pass into the dorsolateral tract of Lissauer where they branch. Within the medial aspect of Lissauer's tract, each fiber bifurcates into an ascending branch extending rostrally for one segment and a descending branch extending caudally for one segment; the total distribution is to approximately three spinal segments. Collaterals from these branches terminate largely in lamina I and to a lesser degree in laminae II and III. In general, the terminal fibers are distributed mainly to the laminae



*Fig. 2.* Schema illustrating (a) the course and termination of dorsal root fibers within the spinal cord (right half of figure) and (b) the major ascending tracts of the spinal cord (left half of figure). The lateral bundle of thin fibers (L) pass into the dorsolateral tract of Lissauer (D.T.L.) and into laminae I, II and III. The medial bundle of heavily myelinated fibers (M) pass into the posterior column and many laminae. The bifurcations of fibers into ascending branches and descending branches within the dorsolateral tract of Lissauer and the posterior column are indicated by the arrows. The ascending tracts include the fasciculus gracilis (F.G.), fasciculus cuneatus (F.C.), posterior spinocerebellar tract (P.S.C.T.), anterior spinocerebellar tract (A.S.C.T.), lateral spinothalamic tract (L.S.T.T.), anterior spinothalamic tract (A.S.T.T.), spinotectal tract (S.T.) and spinoreticular tract (S.R.T.) (medial to A.S.T.T.).

at the segmental level of entrance and to the same laminae, but in lesser numbers, in the segmental level above and the segmental level below the level of entrance.

The myelinated fibers of the medial bundle pass through the posterior funiculus adjacent to the gray matter and the medial portions of laminae II, III and IV of the posterior horn. The main fibers of the collateral branches 1. may extend to and terminate in the gray matter at the spinal level of entrance, 2. may ascend or descend within the posterior columns and terminate in the gray matter at other spinal segments, or 3. may ascend terminate in nuclei of the medulla (fig. 2). Many fibers recurve in lamina IV and extend in a radial pattern dorsally into laminae II, III and IV; a few fibers may reach lamina II, but most fibers terminate mainly in laminae III and IV (nucleus



proprius). Many fibers project and terminate in the medial and central regions of laminae V, VI and VII. Some fibers continue anteriorly in two patterns: one courses through the medial aspect of lamina VII and the other through central lamina VII (fig. 2). These fibers terminate 1. in laminae VIII and medial lamina IX, and 2. in lateral lamina IX respectively. Each dorsal root fiber of the lateral bundle has collaterals, which ascend and descend one or two spinal segments above and below the level of entrance before distributing in the above patterns. Collaterals of the dorsal root fibers terminate in the central cervical nucleus, thoracic nucleus of Clarke and intermediomedial nucleus. The intermediomedial nucleus may be the terminal nucleus for visceral afferent fibers [SZENTAGOTHAÏ, 1966]. The intermediolateral nucleus, which is the nucleus of origin of the preganglionic sympathetic neurons, does not receive any direct dorsal root fibers. The thoracic nucleus of Clarke receives terminal collaterals from the fifth cervical through the sacral roots; each root may project to the thoracic nucleus from eight segmental levels above to four segmental levels below the spinal level of entrance [SHRIVER, STEIN and CARPENTER, 1968; CARPENTER, STEIN and SHRIVER, 1968]. The fibers in roots of the first four cervical segments do not project to the thoracic nucleus. The nucleus of the spinal accessory nerve receives terminal collaterals from fibers of the second through the fifth cervical dorsal roots [SHRIVER, STEIN and CARPENTER, 1968].

The dorsal root fibers terminate somatotopically within laminae III and IV. The fibers of neurons innervating the more distal and postaxial regions of the upper extremity terminate medially and those innervating the more proximal and preaxial regions of the upper extremity terminate laterally within laminae III and IV of the cervical (brachial) enlargement [STERLING and KUYPERS, 1967]. The terminations of the dorsal root fibers within laminae V and VI are not somatotopically organized.

On the basis of anatomical evidence [SPRAGUE and HA, 1964] and physiological evidence [ECCLES, ECCLES and LUNDBERG, 1960], it is indicated that the dorsal root fibers of groups Ia, Ib and III muscle afferents and some cutaneous afferents terminate in laminae V and VI. Laminae IV, V and VI respond to cutaneous stimulation and lamina VI to joint movements [WALL, 1967]. Fibers of the Ia and Ib afferents and from the stretch receptors terminate in the thoracic nucleus of CLARKE [LLOYD and MCINTYRE, 1950].

*Posterior columns.* The course and termination of the dorsal root fibers of the rhesus monkey within the posterior columns are based primarily upon the studies of FERRARO and BERRARA [1935], WALKER and WEAVER [1942],

SHRIVER, STEIN and CARPENTER [1968], and CARPENTER, STEIN and SHRIVER [1968]. The dorsal root fibers pass from the medial bundle into the posterior columns where they divide into a transverse collateral branch, described above, a long ascending branch and a short descending branch. Fibers from all cervical and the upper seven thoracic roots ascend in the fasciculus cuneatus; most of these fibers are derived from the roots of the brachial enlargement. Within the fasciculus, there is a general segregation with extensive overlap of the fibers according to their segmental origin (fibers from the thoracic levels are located medial to those from cervical levels). Fibers from the lower five thoracic, lumbar, sacral and coccygeal roots ascend in the fasciculus gracilis; most of these are derived from the roots of the lumbar enlargement. The segregation of the fibers within the fasciculus is indicated with the more caudally derived fibers located medially and the more rostrally derived fibers located more laterally. The ascending fibers from all cervical and upper thoracic segments terminate somatotopically in both the cuneate nucleus and the accessory cuneate nucleus of the medulla [SHRIVER, STEIN and CARPENTER, 1968]. A few fibers from the thoracic 8 through lumbar 1 may terminate in the cuneate nucleus [CARPENTER, STEIN and SHRIVER, 1968]. The accessory cuneate nucleus may receive direct projection from thoracic 8 [WALKER and WEAVER, 1942] but not from thoracic 5 and 6 [FERRARO and BERRERA, 1942]. The projections to the accessory cuneate nucleus from the upper cervical roots were described by SHERRINGTON [1893]. The long ascending fibers of the fasciculus gracilis, all of which are derived from the dorsal roots of thoracic 8 through the coccygeal segments, terminate with somatotopic yet partially overlapping patterns within the nucleus gracilis.

The descending collateral branches project caudally from one to four segments generally but may extend for as many as eight segments; they do not descend in a compact bundle, as classically described, but rather form oblique bands [CARPENTER, STEIN and SHRIVER, 1968]. These descending fibers may terminate in the thoracic nucleus of Clarke and in the medial parts of laminae VI and VII.

Fibers from the dorsal roots of the upper five cervical levels project to the central cervical nucleus of lamina VII, the intermediate nucleus of the upper cervical levels and medulla, and the supraspinal nucleus. The central cervical nucleus and the intermediate nucleus probably belong to the same nuclear complex [SHRIVER, STEIN and CARPENTER, 1968]. The supraspinal nucleus is the nucleus of origin of motor fibers passing through the ventral root of the first cervical nerve. Some dorsal root fibers may ascend and terminate in several other nuclei of the medulla [SHRIVER, STEIN and CARPENTER, 1968];

these include the nucleus solitarius, nucleus of Roller, nucleus intercalatus, nuclei of the parvocellular reticular formation and the magnocellular portion of the spinal trigeminal nucleus.

*Spinal projections of the substantia gelatinosa.* Neurons with cell bodies in lamina II of the substantia gelatinosa give rise to propriospinal fibers which project to the lateral portion of Lissauer's tract and the adjacent dorsal part of the lateral funiculus; these tracts bridge distances of five to six spinal segments before terminating in laminae I, II and III [SZENTAGOTHAI, 1964]. The substantia gelatinosa of the two sides are interconnected by fibers which project from the substantia gelatinosa of one side through the posterior gray commissure to the contralateral substantia gelatinosa [SZENTAGOTHAI, 1964].

#### ASCENDING PATHWAYS

*Spinothalamic tracts.* The course of the spinothalamic tracts were experimentally demonstrated in the chimpanzee in WALKER's [1937, 1938] studies. The lateral spinothalamic tract (pain and temperature) and the anterior spinothalamic tract (light touch) have been classically described as originating from cell bodies located in the proper sensory nucleus (laminae III and IV) of the posterior horn decussating through the anterior white commissure. This view has been not substantiated. As early as 1952, PEARSON demonstrated that the neurons in the proper sensory nucleus do not have axons which cross in the anterior white commissure. Recent evidence suggests that these tracts have their neurons of origin located in laminae VI, VII and possibly VIII [SZENTAGOTHAI, 1964]. Axons from these neurons pass through the anterior white commissure and ascend as the spinothalamic tracts. The fibers in the lateral spinothalamic tract, either through collateral branches or terminal branches, make synaptic connections 1. with nuclei of the brain stem reticular formation, 2. with the parafascicular nucleus and central lateral nucleus of the intralaminar thalamic nuclei (paleospinothalamic pathway), and 3. with ventral posterolateral thalamic nucleus (neospinothalamic pathway) [MEHLER, FEFERMAN and NAUTA, 1960; BOWSHER, 1961; MEHLER, 1962]. The fibers of the anterior spinothalamic tract ascend either with the medial lemniscus or join with the lateral spinothalamic tract to form the spinothalamic tract; these fibers terminate in the ventral posterolateral nucleus of the thalamus. The precise organization of the posterior horn with regards to the terminations of the dorsal root fibers, the interneurons and the neurons of origin of the

spinothalamic tracts has not been established. This circuitry is important in the processing of the afferent input. The lateral spinothalamic tract is somatotopically organized with the fibers related to input from the more caudal dermatomes being located more laterally and dorsally within the tract than those from more rostral dermatomes [WEAVER and WALKER, 1941]. The proportion of fibers ascending in the anterolateral quadrant of the spinal cord and terminating in the thalamus (mainly ventral posterolateral nucleus) is greater in the chimpanzee than in the rhesus monkey or cat [MEHLER, FEFERMAN and NAUTA, 1960].

*Posterior column – Medial lemniscal pathway.* The posterior column is composed of the fasciculus gracilis and the fasciculus cuneatus (fig. 2). This somatotopically organized pathway conveys the general somatic modalities such as the tactile, kinesthetic, vibratory and two-point discriminatory senses. The medial lemniscus is that bundle of the pathway within the brain stem relaying from the nuclei gracilis and cuneatus to terminate somatotopically in the contralateral ventral posterolateral nucleus of the thalamus. The posterior columns are discussed in the section 'Course and termination of the posterior root fibers within the spinal cord'.

*Spinocerebellar pathways.* In mammals, there are at least four pathways projecting directly or indirectly from the spinal cord to the cerebellum; they include the posterior spinocerebellar tract, the anterior spinocerebellar tract, the cuneocerebellar tract and the rostral spinocerebellar tract. Only the rostral spinocerebellar tract, which has been described only in the cat, has not been definitely identified in the primates [OSCARSSON, 1964].

The anterior spinocerebellar tract is probably derived from cells in the base and neck of the posterior horn and the zona intermedia (laminae V, VI and VII) of the fourth and fifth lumbar levels [HUBBARD and OSCARSSON, 1962] or from scattered cells located in the dorsolateral portion of the anterior horn [HA and LIU, 1968]. COOPER and SHERRINGTON [1940] suggest that this tract originated from spinal 'border cells' located along the anterior margin of the anterior horn of the lumbosacral segments of the spinal cord of the monkey. The presence of these cells was confirmed by SPRAGUE [1953] and others; current evidence suggests that these COOPER-SHERRINGTON cells may be the source of only a few spinocerebellar tract fibers [HA and LIU, 1968]. This tract receives influences from the group Ia (Golgi tendon organ) afferents and the flexor reflex afferents of the lower extremity [OSCARSSON, 1965]; there is no upper extremity component. The somatotopic organization of this tract



is similar to that of the lateral spinothalamic tract which lies deep to it; the lumbar and sacral segments are represented and located superficial and slightly ventromedial to the lumbar and sacral segments of the lateral spinothalamic tract [Yoss, 1953]. This is primarily a cross tract (decussating through the anterior white commissure) which ascends through the spinal cord, medulla, pons, midbrain and superior cerebellar peduncle before terminating in the anterior lobe, pyramis, uvula and declive of the cerebellum [Yoss, 1953; VACHANANDA, 1959].

The rostral spinocerebellar tract in the cat [OSCARSSON, 1964] is presumed to be the equivalent to the anterior spinocerebellar tract for the upper extremity. It has not, as yet, been identified in the primates. The cells of origin are probably present in segments rostral to cervical 8; they presumably give rise to an uncrossed tract located in the white matter in the anterior aspect of the spinal cord.

In the monkey, the posterior spinocerebellar tract originates from the thoracic nucleus of Clarke of lamina VII located in cervical 8 through lumbar 3 spinal segments; a single dorsal root may distribute its fibers to the thoracic nucleus in four to ten spinal segments [SHRIVER, STEIN and CARPENTER, 1968; CARPENTER, STEIN and SHRIVER, 1968]. This tract is primarily an uncrossed somatotopically organized ascending tract located in the lateral funiculus lateral to the lateral corticospinal tract; it passes through the spinal cord, medulla and the inferior cerebellar peduncle before terminating in the anterior lobe and declive of the cerebellum [Yoss, 1952; VACHANANDA, 1959].

In the monkey, the cuneocerebellar tract is included in the pathway composed of the sequence of 1. dorsal root fibers from thoracic 7 through cervical 1, which ascend in the fasciculus cuneatus and terminate in the accessory cuneate nucleus in a somatotopic manner [SHRIVER, STEIN and CARPENTER, 1968] and 2. fibers from the accessory cuneate nucleus which ascend as uncrossed projections through the inferior cerebellar peduncle before terminating in the anterior lobe of the cerebellum. This pathway is considered to be the cephalic equivalent of the posterior spinocerebellar tract, with the accessory cuneate nucleus being the rostral equivalent of the thoracic nucleus of Clarke.

The spinocerebellar pathways convey information from proprioceptive receptors in the neck, trunk and extremities to the cerebellum.

*Spino-cervico-thalamic pathway.* The spino-cervico-thalamic pathway is a system primarily for the transmission of tactile and kinesthetic information; it differs from the spinothalamic pathways and the posterior column – medial lemniscal pathway in that an additional relay nucleus, the lateral cervical

nucleus, is interposed between the spinal cord nuclei receiving the direct input via the dorsal roots and the nucleus of termination in the thalamus [HA and LIU, 1966]. Although this pathway has not been experimentally analyzed in the primates, it is probably present in all primates including the chimpanzee, because the relay nucleus of this pathway, the lateral cervical nucleus, is found in primates including man [HA and MORIN, 1964; MIZUNA, NAKANO and IMAIZUMI 1967; and others]. The details of this pathway were established by experimental studies in the cat [MORIN, 1955; HA and LIU, 1966; and others]. The lateral cervical nucleus is present in the lower medulla and the upper two cervical segments in the lateral funiculus ventrolateral to the posterior horn. The spino-cervico-thalamic pathway conveys, along with the classical spinothalamic system and the posterior column – medial lemniscal system, neural information from the spinal cord to the contralateral ventral posterolateral thalamic nucleus. The influences from the afferent fibers of the dorsal roots reach the lateral cervical nucleus indirectly via three routes: 1. collateral branches of the posterior spinocerebellar tract, 2. collateral branches of the anterior spinocerebellar tract, and 3. fibers from neurons in the dorsal horn of the lower lumbar and sacral spinal segments. The fibers from the lateral cervical nucleus decussate to the contralateral side in the upper cervical spinal cord and lower medulla ascend through the brain stem and terminate in the ventral posterolateral nucleus of the thalamus.

*Spinoreticular, spinoolivary and spinotectal tracts.* Other tracts projecting from the spinal cord to the brain stem, especially via the deep strata of the white matter in the anterior half of the spinal cord, include the spinoreticular tract, the spinoolivary tract and the spinotectal tract. The course and termination of the first two tracts are comprehensively reviewed by MEHLER, FEFERMAN and NAUTA [1956, 1960], and MEHLER [1962], who analyzed these tracts in the chimpanzee.

The ascending spinal fibers in the anterior funiculus and antero-lateral funiculus distribute massively to several nuclei of the medullary and pontine reticular formation and to a lesser degree to the lateral regions of the mesencephalic central gray matter and the deep strata of the superior colliculus. The spinoreticular tract is composed of those fibers terminating in the nuclei of the reticular formation and the mesencephalic periventricular gray; these fibers are integrated into the reticular system. The spinotectal tract is composed of those fibers projecting to the midbrain tectum [LEGROS CLARK, 1936]. The spinoreticular tract is composed mainly of fibers projecting from the spinal cord and terminating in the bulbar reticular formation and such

cranial nerve nuclei as the motor nuclei of the fifth and seventh cranial nerves [MEHLER, FEFERMAN and NAUTA, 1960] and of collateral branches from the spinothalamic tracts.

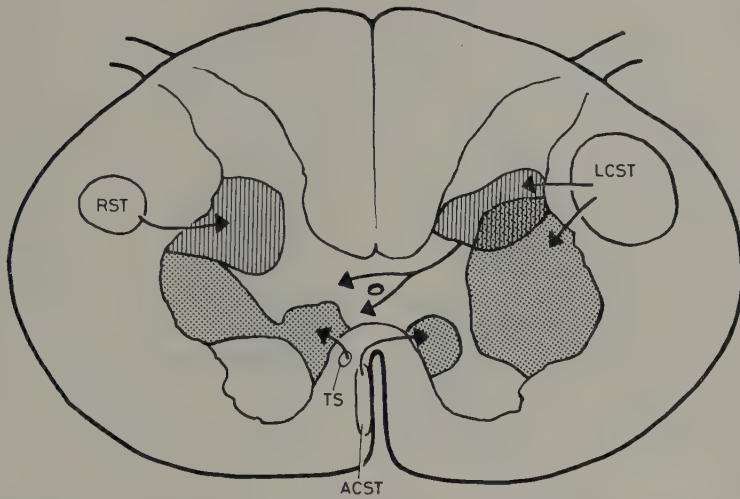
The spinoolivary tract in the monkey [MAY, 1906] is comprised of collateral fibers of spinoreticular fibers projecting to the paleo-olivary nuclei [CAJAL, 1906]. There are no spinoolivary fibers projecting to the neo-olivary nucleus. Most of the fibers in the monkey are derived from the ipsilateral side below thoracic 7 [MEHLER, FEFERMAN and NAUTA, 1960; BOWSHER, 1962]. The projection to the paleo-olive has not been demonstrated in the chimpanzee [MEHLER, FEFERMAN, and NAUTA, 1960].

*Spinovestibular tract.* Ascending fibers from neurons in the gray matter of the spinal cord terminate in the inferior vestibular nucleus.

#### DESCENDING TRACTS

The descending supraspinal tracts from the brain to the spinal cord originate from the cell bodies of neurons located 1. in the cerebral cortex (corticospinal tract), 2. in the midbrain (rubrospinal tract, tectospinal tract and interstitio-spinal tract), and 3. in the lower brain stem (pontine or medial reticulospinal tract, medullary or lateral reticulospinal tract and vestibulospinal tracts).

The following general conclusions regarding the descending tracts terminating in the spinal cord are reviewed and outlined by PETRAS [1966] and NYBERG-HANSEN [1966]: 1. The tracts from the cerebral cortex and the midbrain, except for the interstitiospinal tract, are composed mainly of fibers which decussate in the brain stem and terminate in the contralateral half of the spinal cord, whereas the descending tracts from the lower brain stem (pons and medulla) are composed mainly of fibers which descend and terminate on the ipsilateral side of the spinal cord. 2. These descending pathways exert their inhibitory and facilitatory influences primarily upon the intrinsic circuits of the spinal cord by synapsing with interneurons (proprio-spinal neurons) within the gray matter [SPRAGUE, 1951]. Some fibers of the corticospinal tracts of the primates terminate directly upon the alpha motor neurons and gamma motor neurons (lamina IX) of the anterior horn [KUYPERS, 1960]. 3. The fibers of the descending tracts terminate largely in two general regions of the gray matter (fig. 3, 4). The tracts descending in the anterior funiculus (vestibulospinal tracts, interstitiospinal tract, medial reticulospinal tract) terminate and synapse in the medial portions of the



*Fig. 3.* Schema illustrating some major descending (motor) supraspinal tracts within the spinal cord and their sites of termination within the gray matter. The fibers of the lateral corticospinal tract (L.C.S.T.) from the 'sensory' cortex terminate in the area with the vertical lines and those from the 'motor' cortex terminate in the stippled area. The anterior corticospinal tract (A.C.S.T.), tectospinal tract (T.S.) and rubrospinal tract (R.S.T.) terminate in the areas designated. The arrows leading from the lateral corticospinal tract from right to left across the midline represent the few corticospinal fibers which recross and terminate in the region of lamina VIII [PETRAS, 1967, see text].

intermediate zone (lamina VII) and in the medial portion of the ventral horn (lamina VIII and adjacent portions of lamina IX). The tectospinal tract terminates in lamina VIII and lateral portions of laminae VI and VII. The tracts descending in the lateral funiculus (corticospinal tract, rubrospinal tract and lateral reticulospinal tract) terminate primarily in the base of the dorsal horn and lateral portions of the intermediate zone (laminae V, VI and VII). In the primates, some fibers of the corticospinal tract terminate in the nucleus proprius (laminae III and IV) and to the motor neurons in the anterior horn (lamina IX). 4. The tracts in the anterior funiculus are probably phylogenetically older than the tracts in the lateral funiculus. The medial reticulospinal tract and the vestibulospinal tracts of the anterior funiculus exert excitatory influences on the extensor reflexes and inhibitory influences on the flexor reflexes (postural tone). The corticospinal tract, lateral reticulospinal tract and rubrospinal tract of the lateral funiculus exert excitatory influences on the flexor reflexes and inhibitory influences on the extensor reflexes; 5. No descending fibers terminate directly within the intermedio-



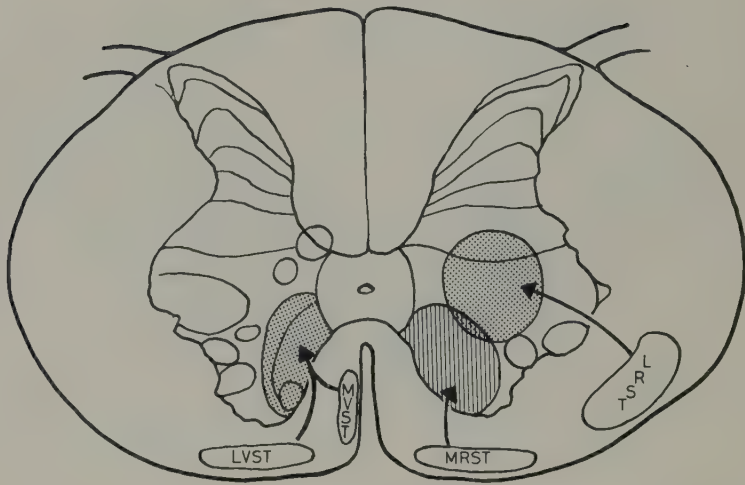


Fig. 4. Schema illustrating some descending (motor) supraspinal tracts within the spinal cord and their sites of termination within the gray matter. The lateral (medullary) reticulospinal tract (L.R.S.T.), medial (pontine) reticulospinal tract (M.R.S.T.), medial vestibulospinal tract (M.V.S.T.) and lateral vestibulospinal tract (L.V.S.T.) terminate in the areas designated. REXED's laminae are outlined.

lateral cell column of lamina VII. This implies that the descending autonomic fibers from the brain stem reticular formation do not synapse directly with the preganglionic sympathetic neurons.

*Corticospinal tracts* (fig. 3). The corticospinal tracts originate from neurons located in wide areas of the cerebral cortex including the precentral gyrus (area 4, 'motor cortex'), the postcentral gyrus (areas 1, 2 and 3), the parietal lobe and adjacent portions of the occipital and temporal lobes. The relation of area 4 and the corticospinal tracts in the chimpanzee was demonstrated by GRÜNBAUM and SHERRINGTON [1901]. The contribution of each cortical region to these tracts has not been analyzed in the chimpanzee. The fibers descend successively through the corona radiata, internal capsule, cerebral peduncle, pons and pyramid; most of the fibers cross over in the pyramidal decussation and descend along with a few uncrossed fibers in the dorsal half of the lateral funiculus as the lateral corticospinal tract throughout the spinal cord. The anterior corticospinal tract in the chimpanzee [LEYTON and SHERRINGTON, 1917; HOFF and HOFF, 1934] descends from the pyramid through the ipsilateral anterior funiculus as far down as the lower thoracic and upper lumbar levels [FULTON and SHEEHAN, 1935]. Many of the fibers of this tract decussate

in the spinal anterior white commissure before terminating in the contralateral gray matter in the dorsomedial region of the anterior horn (dorsal portion of lamina VIII and adjacent lamina VII). HOFF and HOFF [1934] state that, in the chimpanzee, 75 to 80% of the fibers of the corticospinal tract terminate in the gray matter of the contralateral side and 20 to 25% in the gray matter of the ipsilateral side. The corticospinal tracts are large in the chimpanzee; LASSEK and WHEATLEY [1945] report that the two pyramids of a chimpanzee contained 807,000 fibers in a total cross-sectional area of  $7.77 \text{ mm}^2$  and the pyramids of man had 1,100,998 fibers in  $11.42 \text{ mm}^2$ . The fibers of the corticospinal tract, as in other primates, is composed of fibers of all sizes from  $1 \mu\text{m}$  to  $20 \mu\text{m}$  in diameter; most of the fibers are less than  $4 \mu\text{m}$  in diameter [VERHAART, 1954]. In general, the corticospinal tracts in the chimpanzee are similar to those in the other anthropoid apes [PETRAS, 1968]. WEIL and LASSEK [1930] estimate that, in man, 55% of all pyramidal fibers terminate in the segments of the cervical enlargement (innervation of the upper extremities), 20% in the thoracic segments and 25% in the segments of the lumbosacral enlargement (innervation of the lower extremities). The terminal fibers of this tract are more numerous in the chimpanzee than in the rhesus monkey and almost as abundant as in man [KUYPERS, 1962, 1964; KUYPERS, FLEMING and FARINHOLT, 1962]. The crossed and uncrossed fibers of the lateral corticospinal tract terminate chiefly, but not exclusively, on neurons of the spinal gray matter in lateral nucleus proprius and lateral basal region of the dorsal horn, lateral intermediate zone and ventral horn – the lateral portions of laminae IV, V, VI, and VII primarily and to a lesser degree laminae VIII and IX [HOFF and HOFF, 1934; CHAMBERS and LIU, 1958; KUYPERS, 1960]. The anterior corticospinal fibers, both crossed and uncrossed, terminate in the dorsomedial ventral horn (dorsal lamina VIII). It is probable that, as in the rhesus monkey, a few crossed lateral corticospinal tract fibers recross the midline via the spinal commissures and terminate in lamina VII and the medial aspect of the ventral horn [PETRAS, 1967]; these fibers from the cortex decussate in the pyramidal decussation and recussate in the commissures of the spinal cord. The cortical projections in the chimpanzee, in terms of specific sites of termination, are probably similar to those described in the rhesus monkey by KUYPERS [1960] and LIU and CHAMBERS [1964]. The fibers from neurons in the pre- and postcentral gyri (per-Rolandic cortex) are distributed to the posterior horn, base of the posterior horn, throughout the intermediate zone and to the lateral horn (laminae IV, V, VI, VII and IX). The fibers to the nucleus proprius (laminae IV, V and VI) arise from the postcentral gyrus while those to the basal posterior horn, inter-

mediate zone and ventral horn (laminae V, VI, VII and IX) arise from the precentral gyrus. Within these laminae the projections are differentially distributed, with the lateral portions of the laminae receiving more terminal fibers than the medial portions [PETRAS, 1968].

Most of the corticospinal terminal branches synapse with interneurons which are intergrated into the intrinsic spinal circuits which, in turn, influence the activity of the alpha and gamma motor neurons. In the chimpanzee, as in other primates, the motor cortex projects some of its fibers directly to the lower motor neurons [KUYPERS, 1960]. The distal muscles of each extremity are innervated by lower motor neurons which receive more of the direct corticospinal connections than do the proximal muscles of each extremity [KUYPERS, 1964]. The facilitatory influences on flexor activity are expressed in the role of the corticospinal pathways in skilled voluntary movements associated with the fractionation of a movement (e.g., independent actions of such segments as the digits). In the chimpanzee, 5% of the corticospinal fibers terminate on the lower motor neurons [KUYPERS, 1960]. The maturation of these direct fibers is not completed until the first months after birth [KUYPERS, 1964]. Direct corticospinal connections with the lower motor neurons of the medial nuclei of lamina IX are sparse; these lower motor neurons innervate the epaxial and hypaxial musculature [PETRAS, 1968]. The corticospinal tract is not somatotopically organized within the spinal cord.

*Rubrospinal tract* (fig. 3). In primates, the rubrospinal tract originates in the nucleus ruber of the midbrain, decussates in the ventral tegmental decussation of the midbrain, descends the brain stem and the entire length of the spinal cord and terminates in the lateral basilar region of the posterior horn and the adjacent zona terminalis [COLLIER and BUZZARD, 1901; METTLER, 1944; KUYPERS, FLEMING and FARINHOLT, 1962; PETRAS, 1967]. This tract is said to be 'poorly developed' in the anthropoids [SCHOEN, 1964]. This is probably incorrect. In the chimpanzee, this tract is composed of fine small-calibered fibers [VERHAART, 1938], which, as in the rhesus monkey, terminate mainly in the central and lateral regions of laminae, V, VI and VII [KUYPERS, FLEMING and FARINHOLT, 1962]. The terminal distribution of this tract overlaps extensively with that of the corticospinal fibers and to a lesser degree with that of fibers of the lateral reticulospinal tract. The rubrospinal tract is somatotopically organized, with the dorsomedian 'forelimb' regions of the nucleus ruber projecting to the cervical enlargement and with the ventrolateral 'hindlimb' region projecting to the lumbosacral enlargement [POMPEIANO and BRODAL, 1957]. No fibers terminate in the anterior horn (lamina IX).

The rubrospinal tract, which is integrated into the corticorubrospinal pathway, acts to increase muscle tone and to inhibit extensor muscle tone; it is said to be functionally correlated with 'skilled voluntary movements'.

*Reticulospinal tracts* (fig.4). The lateral (medullary) reticulospinal tract originates primarily from the nucleus reticularis gigantocellularis and nucleus reticularis ventralis of the medulla and partially from the nucleus reticularis pontis caudalis [KUYPERS, FLEMING and FARINHOLT, 1962]. The tract is primarily composed of ipsilateral fibers and of a few crossed fibers, which descend in the ventromedial aspect of the lateral funiculus to all levels of the spinal cord. Its small-calibered fibers terminate in the central and lateral portions of laminae VI and VII and adjacent parts of lamina IX. This pathway acts to facilitate the flexor reflexes and to inhibit the extensor reflexes. It has a wider distribution than the medial reticulospinal tract has [PETRAS, 1967].

The medial (pontine) reticulospinal tract originates primarily from the nucleus reticularis pontis caudalis and oralis [TORVIK and BRODAL, 1957]. The tract is primarily composed of ipsilateral fibers and a few crossed fibers, which descend in the anterior funiculus to all levels of the spinal cord [KUYPERS, FLEMING and FARINHOLT, 1962]. Its small-calibered fibers terminate mainly in lamina VIII and in adjacent areas of laminae VII and IX. This pathway contributes to postural tone by acting to facilitate the extensor reflexes and to inhibit the flexor reflexes.

The reticulospinal tracts, which are incorporated into the corticoreticulospinal pathways, are not somatotopically organized.

Some reticulospinal fibers convey the suprasegmental influences, which act upon the spinal neurons of the autonomic nervous system.

*Vestibulospinal tracts* (fig.4). The (lateral) vestibulospinal tract is small in the chimpanzee [SCHOEN, 1964]. It is composed of large-calibered fibers which originate in the lateral (Deiter's) vestibular nucleus, descend exclusively in the ipsilateral anterior margin of the spinal cord and terminate in lamina VIII and adjacent central and medial portions of lamina VII in all spinal segments [KUYPERS, FLEMING and FARINHOLT, 1962; NYBERG-HANSEN, 1966]. Most of the fibers terminate upon interneurons in the segments of the cervical enlargement and the lumbosacral enlargement. This tract is somatotopically organized, with the rostroventral portion of the lateral vestibular nucleus projecting to the cervical spinal segments and the dorsocaudal portion projecting to the lumbosacral segments [POMPEIANO and BRODAL, 1957].



The fibers of the medial vestibulospinal tract originate exclusively in the medial vestibular nucleus [NYBERG-HANSEN, 1966] and descend bilaterally with the medial longitudinal fasciculus as far down as midthoracic levels [FERRARO, PACELLA and BARRERA, 1940]. The fibers descending on the ipsilateral side outnumber those few descending on the contralateral side; they terminate in lamina VIII and the adjacent portions of lamina VII.

The vestibulospinal tracts contribute to postural tone by acting to facilitate extensor muscle tone and to inhibit flexor muscle tone. The area of the terminal distribution of these tracts are less than for the medial reticulospinal tract [PETRAS, 1967].

*Tectospinal tract and interstitiospinal tract* (fig. 3). These tracts have not been described in the chimpanzee. In the rhesus monkey, the fibers of the tectospinal tract originate from neurons in the fifth layer of the superior colliculus and those of the interstitiospinal tract originate from neurons in the interstitial nucleus of Cajal in the midbrain [KUYPERS, 1962, 1964]. The nucleus of Darkschewitsch of the midbrain apparently does not project descending fibers to the spinal cord [NYBERG-HANSEN, 1966]. The fibers of the tectospinal tract cross over in the dorsal tegmental decussation of the midbrain and descend in the medial longitudinal fasciculus (predorsal bundle) in the anterior funiculus as far as the lowest cervical levels. They terminate in the medial aspect of lamina VII and adjacent regions of laminae VI and VIII, and in central and lateral regions of lamina VII. The majority of its fibers terminate in the upper four cervical segments in the cat [ALTMAN and CARPENTER, 1961; NYBERG-HANSEN, 1966].

The fibers of the interstitiospinal tracts descend bilaterally (mainly as ipsilateral projections) as far down as the sacral levels [KUYPERS, 1964; NYBERG-HANSEN, 1966]. They terminate in the dorsal aspect of lamina VII and adjacent lateral areas of laminae VI and VII. The tectospinal tract, interstitiospinal tract and the medial vestibulospinal tract are collectively called the medial longitudinal fasciculus. These tracts do not have any fibers terminating on the lower motor neurons of lamina IX.

#### ORIGIN OF THE VENTRAL (MOTOR) ROOTS

The cell bodies of the somatic efferent root neurons are located in lamina IX of the anterior horn, while those of the visceral efferent root fibers (of the autonomic nervous system) are located in the intermediolateral nucleus of

lamina VII in the thoracic and upper lumbar segments (sympathetic outflow) and in the intermediate zone (lamina VII) and anterior horn (lamina IX) of the middle sacral segments (parasympathetic outflow). The motor fibers from the spinal cord emerge through the anterolateral sulcus to form the ventral roots of the spinal nerves.

SERGI [1926–27] describes and illustrates the motor nuclei in each of the segmental levels of the anterior horn of the spinal cord of the chimpanzee. These nuclei appear to be basically similar to those described in man and in the rhesus monkey by REED [1940] and SPRAGUE [1948, 1951]. The cell bodies of the motor neurons are not organized in nuclear groups which extend as continuous columns throughout the cord in the rhesus monkey, rather the nuclei are discontinuous columns [SPRAGUE, 1948]. The ‘so-called’ medial column contains the neurons innervating the axial musculature whereas the lateral columns innervate the appendicular musculature of the extremities [SPRAGUE, 1948]. It has been assumed that the gamma motor neurons have small cell bodies and the alpha motor neurons have large cell bodies.

Although there is a somatotopic organization of the motor neurons within the anterior horn [ROMANES, 1951, 1964], the definitive study of the somatotopic organizations of these neurons in the spinal cord of the chimpanzee, monkey or even the cat has not, as yet, been completed. On the basis of morphology and topology it is not possible to identify the functional role of each cell group [SPRAGUE, 1951]; the relation between the somatotopic organization and the functional role each cell group can be determined from experimental analyses. In this regard the experimental data of STERLING and KUYPERS [1967] in the cat is pertinent. They conclude that the neuronal organization of the anterior horn in the brachial (cervical enlargement) region is similar to that described by REED [1940] in the monkey. The cell bodies of the alpha motor neurons innervating the intrinsic flexor muscles of the forelimb are aligned as longitudinally organized groups in the dorsolateral region of the lateral motor neuronal cell groups; those innervating the intrinsic extensor motor neuron are similarly aligned ventral to the flexor motor neurons; and those innervating the girdle musculature are aligned further ventrally and medially. The motor neurons belong to groups which extend over several segments of the brachial plexus. The motor neurons of the distal intrinsic limb musculature tend to lie in more caudal segments of the brachial cord and those innervating proximal intrinsic limb muscles are located more rostrally. The arrangements in the lumbosacral cord are more complex than that in the brachial cord; the same general patterns are present in both the brachial cord and the lumbosacral cord.

The anatomical organization of motor neuron groups as longitudinally organized groups oriented parallel to the long axis of the spinal cord is supported by studies indicating that the arborization of the dendrites of the motor neurons are also oriented in the longitudinal plane [LARUELLE, 1948; SCHEIBEL and SCHEIBEL, 1966; STERLING and KUYPERS, 1967]. Furthermore the longitudinally organized motor neuron groups have specific functional parameters related to specific movements – flexion, extension, abduction and adduction [CREED and SHERRINGTON, 1926; STERLING and KUYPERS, 1967].

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Authors' address: Dr. CHARLES R. NOBACK and SONYA K. SIMENAUER, Department of Anatomy, Columbia University, 630 West 168th Street, New York, NY 10032 (USA).

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# POSTURAL, PROPULSIVE, AND PREHENSILE CAPABILITIES IN THE CHEIRIDIA OF CHIMPANZEES AND OTHER GREAT APES

RUSSELL H. TUTTLE

Department of Anthropology and Committee on Evolutionary Biology  
University of Chicago, Chicago, IL

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## I. INTRODUCTION

Common chimpanzees (*Pan troglodytes*) occupy a diversity of habitats varying in biotope from tropical rain forest to forest savanna and deciduous woodland [NAPIER and NAPIER, 1967]. Except perhaps in areas where gardens are available for raiding, the daily fare of chimpanzees is gathered mainly in trees. Chimpanzees build nests in trees at night.

Although in some situations foraging and fleeing chimpanzees may pass sporadically from the branches of one tree into those of the next, they generally move from one feeding or nesting site to another on the ground. Concordantly, the hands and feet of *Pan troglodytes* evidence adaptive compromises between the requisites of arboreal climbing and those of terrestrial locomotion.

In comparison with chimpanzees, gorillas (*Pan gorilla*) represent the advanced development of ground-dwelling, knuckle-walking apes whereas the more distantly related orangutan (*Pongo pygmaeus*) demonstrates the culmination in a large-bodied ape of trends toward strict arboreality.

Further, when *Pan troglodytes* is compared with *Pan gorilla* and *Pongo pygmaeus*, the nature of the evolutionary compromises in the manual and pedal cheiridia are exhibited notably in the range of potential joint movement, the development of major groups of muscles, and the proportions and configuration of bones [TUTTLE, 1967, 1969, and in press a and b].

The purpose of this report is to review the results of comparisons and correlations of the motile behavior and some morphological and functional features in the cheiridia of *Pan troglodytes*, *Pan gorilla* and *Pongo pygmaeus* in order to elucidate the particular adaptive mode of the first of these three taxa.<sup>1</sup>

In order to evaluate properly the nature of bone-ligament-muscle relationships in supporting and locomotive postures, the range of passive movement in joints should be determined and compared with normal close-packed positions of the joints in active animals. Clearly although studies on passive animals indicate possible joint positions and range of motion, these rarely approximate closely the close-packed positions that are utilized in static and dynamic postures of mobile animals. However, studies on passive animals may reveal unexpected potentialities for movement in joints that might not be observed in caged animals and that might be observed only rarely in free-ranging animals.

1 More detailed accounts of the materials, methods and results of the primary studies upon which this review is based have been presented elsewhere [TUTTLE, 1967, 1969, and in press a and b] and are in preparation for publication.

Once the potential range of motion is known for a joint, the biomechanical bases of its role(s) in support and movement may be sought more profitably. For instance, in joints that exhibit restricted motion in passive (i.e. anesthetized and tranquilized) animals it may be assumed that osseous and ligamentous structures are major limiting factors. But as joints evidence increasing potential ranges of motion, it may be assumed that muscles are probably involved more importantly in maintaining their integrity during stance and locomotion.

Presently there are no techniques for accurately determining the relative force exerted by contracting muscles. Many factors, such as the contractile properties of muscle fibers, motor unit architecture and innervation, internal arrangement of fibers, attachments in relation to the axis of motion and concordantly the movement of this axis during joint excursion, contribute to the proficiency of a contracting muscle. Although the mass of a muscle or potential functional group of muscles reflects inadequately the complexities and subtleties of its activities, this dimension is more valuable than traditional 'naked eye' assessments of muscle development and concordant inferred functional importance.

Similarly, the proportional dimensions of bones and the relative development of bony processes proffer only an indication of possible functional importance in the adaptive complex of the animal. Frequently, detailed information is needed on the arrangement of organic and inorganic materials within the bone in order to assess its ability to withstand the compressive and tensile stresses existent in static and locomotive postures [OXNARD, 1967, 1968].

But just as few scientists would deny the value of quantitative studies on the external dimensions of bones, so they might expect to obtain some insights into the functional and adaptive value of major muscle groups by considering results of systematic quantitative studies on their relative mass.

In tables I-VI are summarized data on the degree of passive movement of manual and pedal joints and the relative masses of major potential functional groups of cheiridial muscles in *Pan troglodytes*.

The succeeding discussions do not constitute a comprehensive review of all studies on relative degrees of joint movement and mass of muscles in the Pongidae. Since other investigators have used a variety of methods that cannot be discussed thoroughly in this communication, I will present a general summary of my own recent work and supplement this with the findings of other investigators, particularly on bones, only to the extent necessary to provide a balanced overview of chimpanzee adaptations.

Table I. Degrees of passive dorsiflexion, abduction, adduction, and volarflexion of the wrist; hyperextension of metacarpophalangeal and metatarsophalangeal joints II-V; and hallucal abduction in *Pan troglodytes*

Dimension	No. of Specimens	Mean	90% Limits	
			Lower	Upper
Wrist: Dorsiflexion	21	40.0	22.7	57.3
Abduction	21	31.0	12.1	49.9
Adduction	21	69.0	47.9	90.1
Volarflexion	21	133.8	118.8	148.8
Metacarpophalangeal joints				
II-V: Hyperextension	10	44.0	20.9	67.1
Metatarsophalangeal joints				
II-V: Hyperextension	10	53.3	32.0	74.6
Hallux: Abduction	10	134.7	121.3	148.1

Table II. Percentage by dry weight of potential functional groups of extrinsic and intrinsic hand muscles in *Pan troglodytes*

Dimension	Adults			Young		
	No. of Specimens	Mean	90% Limits Lower Upper	No. of Specimens	Mean	90% Limits Lower Upper
Percentage of total forearm mm.:						
Total extrinsic flexors	10	58.5	56.5 60.5	7	60.0	57.3 62.7
Extrinsic flexors of digits	10	41.6	38.5 44.7	7	43.7	36.4 51.0
Flexors of wrist	10	16.9	13.4 20.4	7	16.3	10.7 21.9
Total extrinsic extensors	10	26.7	24.4 29.0	7	25.8	22.9 28.7
Extrinsic extensors of digits II-V	10	8.8	7.7 9.9	7	8.9	7.4 10.4
Extensors of wrist	10	11.9	10.0 13.8	7	11.3	8.3 14.3
Extensors of digit I	10	6.0	5.1 6.9	7	5.7	4.6 6.8
Total pronators	10	7.5	4.8 10.2	7	7.7	6.3 9.1
Supinator	10	7.3	6.1 8.4	7	6.5	5.0 8.0
Percentage of total intrinsic hand mm.:						
Total palm muscles	15	60.2	55.0 65.4	7	59.9	52.6 67.2
Dorsal interossei	15	40.0	36.0 44.0	7	39.2	33.2 45.2
Palmar interossei	15	12.6	10.1 15.1	7	13.0	9.5 16.5
Lumbricals	15	7.6	4.8 10.4	7	7.7	4.8 10.6
Hypothenar eminence	15	15.7	12.6 18.8	7	15.4	10.8 20.0
Total intrinsic thumb muscles	15	24.1	19.6 28.6	7	24.7	17.0 32.4
Thenar eminence	15	13.9	10.6 17.2	7	13.1	8.1 18.1
Adductor pollicis	15	10.2	7.6 12.8	7	11.6	8.4 14.8

Table III. Ratios comparing the relative mass of potential functional groups of extrinsic and intrinsic hand muscles in *Pan troglodytes*

Dimension	Adult	90% Limits			Young	90% Limits		
	No. of Specimens	Mean	Lower	Upper	No. of Specimens	Mean	Lower	Upper
Extrinsic hand muscle ratios:								
<u>Total flexors <math>\times 100</math></u>	10	219.4	196.0	242.8	7	233.3	197.8	268.8
Total extensors								
<u>Wrist flexors <math>\times 100</math></u>	10	143.3	100.4	186.2	7	144.7	109.8	179.6
Wrist extensors								
<u>Flexor digitorum profundus <math>\times 100</math></u>	10	132.7	109.6	155.8	7	144.3	106.1	182.5
Flexor digitorum superficialis								
<u>Pronators <math>\times 100</math></u>	10	104.1	59.6	148.6	7	119.3	86.5	152.1
Supinator								
Intrinsic hand muscle ratios:								
<u>Muscles preaxial to digit III <math>\times 100</math></u>	15	139.3	115.9	162.7	7	135.2	102.0	168.4
Muscles postaxial to digit III								
<u>Dorsal interossei <math>\times 100</math></u>	15	66.5	61.7	71.3	7	65.5	61.2	69.8
Total palm muscles								
<u>Palmar interossei <math>\times 100</math></u>	15	20.9	17.1	24.7	7	21.6	16.9	26.2
Total palm muscles								
<u>Lumbricals <math>\times 100</math></u>	15	12.5	8.2	16.8	7	12.9	7.8	18.0
Total palm muscles								
<u>Adductor pollicis <math>\times 100</math></u>	15	42.3	34.4	50.2	7	47.3	40.0	54.6
Total thumb muscles								

## II. LOCOMOTOR MODES

Whether in trees or on the ground chimpanzees are basically quadrupedal in locomotor posture (fig. 1). In terrestrial progression, chimpanzees exhibit symmetrical gaits that HILDEBRAND [1967, p. 125] has described as predominantly 'trot' and 'diagonal-sequence, diagonal couplet'. The analysis by HILDEBRAND of gait formulas for captive *Pan troglodytes* demonstrates that during walking strides the hindlimbs are in contact with the ground for periods equal to, or more frequently, somewhat longer than the forelimbs. When moving at moderate to rapid rates, chimpanzees tend to take long steps forward with the hindlimbs by markedly flexing the hip joint and rotating the ipsilateral side forward. Interference of the hindlimb with the forelimb is avoided during a stride by passing each foot to the same side of the respective hand [HILDEBRAND, 1967]. Similarly the length of the forelimb



Table IV. Percentage by dry weight of potential functional groups of extrinsic and intrinsic foot muscles in *Pan troglodytes*

Dimension	No. of Specimens	Mean	90% Limits	
			Lower	Upper
Percentage of total leg mm.:				
Plantar flexors	7	43.9	38.9	48.9
Extrinsic digital flexors	7	15.4	13.3	17.5
Dorsiflexors	7	16.1	12.6	19.6
Extrinsic digital extensors	7	6.2	4.6	7.8
Evertors	7	11.1	9.7	12.5
Invertors	7	19.4	15.3	23.5
Popliteus	7	3.9	3.1	4.7
Percentage of total intrinsic foot mm.:				
Total interosseous and lumbrical muscles	7	24.5	17.4	31.6
Dorsal interossei	7	15.8	12.0	19.6
Plantar interossei	7	5.4	3.8	7.0
Lumbricals	7	3.3	1.2	5.4
Short flexors of digit V	7	9.2	6.9	11.5
Total intrinsic hallucal muscles	7	47.7	40.1	55.3
Short hallucal flexors	7	26.5	17.2	35.8
Adductor hallucis	7	21.2	14.4	28.0
Short digital flexors	7	9.1	4.9	13.3
Short digital extensors	7	9.5	6.1	12.9

Table V. Ratios comparing the relative mass of potential functional groups of intrinsic foot muscles in *Pan troglodytes*

Dimension	No. of Specimens	Mean	90% Limits	
			Lower	Upper
Muscles preaxial to digit III $\times 100$	7	279.7	183.5	375.9
Muscles postaxial to digit III				
Dorsal interossei $\times 100$	7	64.8	61.5	68.1
Total lumbrical and interosseous muscles				
Plantar interossei $\times 100$	7	21.9	18.9	24.9
Total lumbrical and interosseous muscles				
Lumbricals $\times 100$	7	13.3	8.4	18.2
Total lumbrical and interosseous muscles				

Table VI. Ratios comparing the relative mass of hand and foot muscles in  
*Pan troglodytes*

Dimension	No. of Specimens	Mean	90% Limits	
			Lower	Upper
Total forearm and hand muscles $\times 100$	6	87.1	77.7	96.5
Total leg and foot muscles				
Total forearm muscles $\times 100$	6	92.3	80.8	103.8
Total leg muscles				
Plantar flexors $\times 100$	6	266.8	202.2	331.4
Wrist flexors				
Antebrachial digital flexors $\times 100$	6	244.4	215.6	273.2
Leg digital flexors				
Total intrinsic foot muscles $\times 100$	6	168.4	151.0	185.8
Total intrinsic hand muscles				
Total intrinsic pedal muscles preaxial to digit III $\times 100$	6	178.7	157.2	200.2
Total intrinsic manual muscles preaxial to digit III				
Total intrinsic pedal muscles postaxial to digit III $\times 100$	6	82.0	61.0	103.0
Total intrinsic manual muscles postaxial to digit III				
Total palm muscles $\times 100$	6	150.4	118.3	182.5
Total pedal lumbrical and interosseous muscles				
Manual dorsal interossei $\times 100$	6	151.6	121.6	181.6
Pedal dorsal interossei				
Palmar interossei $\times 100$	6	150.5	84.9	216.1
Plantar interossei				
Manual lumbricals $\times 100$	6	148.3	76.3	220.3
Pedal lumbricals				
Total hallucal flexor, abductor and adductor mm $\times 100$	6	334.8	247.7	421.9
Total thumb muscles				
Short hallucal flexors $\times 100$	6	322.8	268.5	377.0
Thenar eminence muscles				

stride may be increased by pronounced protraction of the remarkably long arms.

Although the main propulsive force appears to be effected by extension (retraction) of the hip and plantarflexion of the ankle joints, retraction of the shoulder also may supply powerful supplementary forces for terrestrial propulsion. The knee joints generally remain flexed during quadrupedal progression. The elbow joints, by contrast, are fully extended during the propulsive strokes of the forelimbs.

The feet are placed basically in a plantigrade posture. The heel and posterior aspect of the sole strike the ground first. Then the weight of the animal is carried mainly on the lateral aspect of the sole. Later and to a



*Fig. 1.* Cheiridial posturing in *Pan troglodytes*.

- a. Adult female chimpanzee in quadrupedal stance. Note knuckle-walking of right hand and plantigrade habitus and curled toes of both feet.
- b. Side view of animal in (A). Note plantigrade habitus of right foot and markedly extended posture of toes on left foot. Right hand is in initial part of the swing phase of the forelimb stride.
- c. Oblique view of knuckle-walking posture in the left hand of an adult male chimpanzee. Note slightly volarflexed posture of the wrist and hyperextended posture of metacarpophalangeal joints II-V.
- d. Plantigrade posturing in right foot of an adult male chimpanzee that is standing bipedally. Note wide abduction of the hallux and curling of digits II-V.

lesser extent the load passes on to the curled digits. In captive animals, the foot may develop a pronounced degree of plantigrady wherein the ventrolateral surfaces of digits II-V and the hallux are apposed to the substratum during resting stance and progression [MORTON, 1922; ELFTMAN and MANTER, 1935]. However, in young chimpanzees and most adults the foot is inverted slightly and the second to fifth toes are flexed, thereby appearing not to bear much weight effectively in the resting or moving animal.

The hands of chimpanzees are placed in knuckle-walking postures wherein the friction pads on the dorsal aspects of the middle phalanges of digits II-V contact the ground [SCHREIBER, 1936; STRAUS, 1940; TUTTLE, 1967]. The wrist may be volarflexed slightly or it may be more directly in line with the forearm. The proximal phalanges generally are hyperextended at the metacarpophalangeal joints, especially when the forelimb is bearing compressive forces. The distal phalanges also may rest on the ground or they may be flexed out of contact with the substratum. The thumb normally does not touch the ground during terrestrial progression and quadrupedal stance.

Due to varying amounts of lateral rotation of the forelimb at the shoulder and radioulnar joints and according to the momentary disposition and individual habits of the animal, the hand may be positioned oblique to the line of progression or, more rarely, perpendicular to this line.

During uneventful bouts of diurnal activity, slow and fast knuckle-walking gaits are generally utilized to move from one tree or area of the forest to another. Asymmetrical gaits such as galloping and bounding, wherein the hindlimbs move forward alternately while the forelimbs move forward together, may be used sporadically by individuals that rush to catch up with a departing group, during play and display, and when the entire group is fleeing from a natural disturbance or intruder.

Brief sequences of terrestrial bipedalism may be exhibited by chimpanzees carrying objects, standing to obtain a better view, and engaging in play, agonistic, and sexual displays. During bouts of slow bipedalism, the arms may hang loosely down and may not swing in time with the legs [REYNOLDS, 1965, p. 60]. The knee and hip joints are flexed and the feet are notably plantigrade in bipedal chimpanzees [ELFTMAN and MANTER, 1935; ELFTMAN, 1944].

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- e. Side view of knuckle-walking posture in the left hand of an adult female chimpanzee. Note elevation of distal phalanges, marked hyperextension of the metacarpophalangeal joints, and slight volarflexion of the wrist (photographs by I. BERNSTEIN and F. KIERNAN, Yerkes Regional Primate Research Center).





Fig. 2. Rapid bipedal running in an adult male *Pan troglodytes*.

- a. Pre-contact part of swing phase in left hindlimb and pre-release part of stance phase in right hindlimb. Note abduction of hallux and curled posture of digits II-V in right foot. The animal maintains partially flexed postures of hip and knee throughout locomotor cycle.
- b. Initial contact part of stance phase in left hindlimb. Load is borne by heel, hallux, and posterior aspect of sole. Digits II and III are free of ground.
- c. Maximum load bearing part of stance phase in left hindlimb. Note marked flexion of knee and dorsiflexion of ankle joint. Load is borne by hallux and sole, especially its lateral aspect. Digits II-V are extended more than in (b) but remain somewhat curled. Right hindlimb is advanced by hip protraction, pelvic rotation, swinging forward of right forelimb and gross forward swinging movements of the entire contralateral side of the body.
- d. Propulsive part of stance phase in left hindlimb. Note greater extension of left knee in comparison with (c). Load is borne mainly by anterolateral aspect of sole. Hallux is flexed and adducted to form an arch whereby the anteromedial aspect of the sole is free from the substratum. Digits II-V are hyperextended at the metatarsophalangeal joints and their distal pads are in contact with the ground. The right hindlimb is advanced far forward and the right forelimb has swung forward by comparison with (c).
- e. Initial contact part of stance phase in right hindlimb. Load is now borne by heel, hallux, and posterior aspect of sole of right foot. Support has been shifted from

Rapid bipedal running is effected by marked side to side rotation of the pelvis while the arms are held out from the body and may be swung synchronously with the crural strides (fig. 2). Thus the bipedal animal waddles along by rocking onto one side while swinging the free side forward with gross body movements and then repeating this sequence with the newly supporting foot as a vantage point.

The predilection for knuckle-walking in chimpanzees is particularly emphasized when they engage in arboreal locomotion. As long as strong supporting branches are available, even high up in trees, chimpanzees remain quadrupedal, and according to the diameter of a limb, may maintain their hands in knuckle-walking postures atop the branch instead of gripping it [REYNOLDS, 1965, p. 62].

On smaller branches the feet and hands function more as prehensile, supporting organs. The feet contact the substratum with the hallux in opposition to the lateral four digits around the branch. The hands may hold the limb in a manner similar to that of the feet, viz. with digit I widely abducted or with it more or less in line with the other digits.

Arm-swinging and suspensory postures are generally utilized only briefly during bouts of foraging, feeding, play and agonism, but these activities are not predominant in the locomotor repertoire of *Pan troglodytes*. All observers of free-ranging chimpanzees concur that whether fleeing from intruders or moving through the forest at leisurely rates, chimpanzees prefer terrestrial pathways and do not traverse the canopy by arm-swinging. In this regard chimpanzees contrast notably with orangutans and gibbons, the latter of which utilize in locomotion a mode of arm-swinging (termed *ricochetal arm-swinging* by TUTTLE, 1969) that is unique among primates and that has an anatomical base distinct from those of the great apes [HOWELL and STRAUS, 1931; STRAUS, 1940; TUTTLE, 1969].

When motivated to transfer from one tree to another, chimpanzees usually descend to the ground. In leisurely descents from tall trees, they generally climb down the trunks. NISSEN [1931, p. 34] noted that chimpanzees appear to have some difficulty descending a tree trunk and that this activity is more time consuming than ascension. If the trunk is very thick, the animals descend feet first, but if the trunk is of small diameter they sometimes descend head first.

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left to right hindlimb not only by propulsive efforts of the left hindlimb but also displacement of the center of gravity of the body forward and to the right by gross body movements (drawings by D. CRAMER, Univ. Chicago).



Fig. 3. Cheiridial posturing in *Pan gorilla*.

a. Juvenile female western gorilla in quadrupedal stance. Note typical knuckle-walking posturing in left hand and plantigrade habitus in right foot. The dorsum of the

Chimpanzees may leave trees hastily by plummeting downward through the foliage after swinging forward on the forelimbs or leaping from atop a branch. In dense forest this may give the impression that they are arm-swinging through the canopy when, in fact, they complete the major segment of their flight on the ground and out sight of the observer.

RAHM [1967] has described a special case in which chimpanzees utilize trees opportunistically to escape from attempts to trap them in nets near the ground. RAHM [1967, p. 203] further noted that when fleeing from net hunters, chimpanzees 'very often ... run upright like gibbons over the branches and jump distances they would not even try under normal conditions'. Similarly, REYNOLDS [1965] noted that chimpanzees 'would often walk bipedally along stout branches supporting themselves from above by holding on to other branches with their hands'.

Available accounts on free-ranging chimpanzees are somewhat ambiguous on the precise manners in which chimpanzees 'jump' across gaps between branches or plummet through the foliage to the ground. NISSEN [1931, p. 21] described one 'short jump' by a chimpanzee into the thick foliage of a neighboring tree after 'bending rapidly at the knee about six times'. But NISSEN also emphasized that most of the 'jumps' that he witnessed were effected *by the forelimbs* as follows: 'the ape first hung by his arms, swung back and forth, and let go on a forward swing' [p. 35]. Both NISSEN [p. 35] and REYNOLDS [1965, p. 58] indicate that chimpanzees 'jump' chiefly in order to rapidly descend to the ground rather than to traverse the canopy.

Chimpanzees are adept in climbing up branchless tree trunks, even those measuring four to five feet in diameter [REYNOLDS, 1965, p. 59; NISSEN, 1931, p. 34]. REYNOLDS [p. 59] described tree-climbing in chimpanzees as follows: '... they climbed upwards by using the arms and long hands to grasp somewhat around and behind the tree trunk, moving each hand up alternately,

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hand is aligned with the line of forward progression by medial rotation of the shoulder and radioulnar joints. The pedal digits exhibit greater extension of the interphalangeal joints than is normally present in chimpanzees.

- b. Knuckle-walking posturing in left hand of juvenile western gorilla. Note hyperextension of metacarpophalangeal joints II-V and prominent interdigital webbing.
- c. Quadrupedal stance in animal (b). Note hyperextension of metacarpophalangeal joints II-V and slight volarflexion of the wrist. The remarkable curling of the pedal digits is a congenital or idiopathic condition and is not typical of gorilla foot posturing (photographs by I. BERNSTEIN and F. KIERNAN, Yerkes Regional Primate Research Center).



while the legs provided the upward thrust, the feet being placed on the side of the tree nearest the chimpanzee, small toes one side, big toe the other'.

Eastern mountain gorillas are primarily quadrupedal and terrestrial (fig. 3), spending approximately 80 to 90% of their waking hours on the ground [SCHALLER, 1963, pp. 81-82]. They climb readily into trees but in a manner more slow and deliberate than that of chimpanzees [SCHALLER, 1963, pp. 81 and 83]. Comparative data on the locomotion of free-ranging western gorillas are not available. However, they are probably somewhat more arboreal than eastern mountain gorillas as evidenced by the fact that they often build tree nests in regions where adequate supports are available [SCHALLER, p. 180].

HILDEBRAND [1967] analyzed gait formulas for *Pan gorilla* that exhibited only the 'trot' among possible symmetrical gaits. Hildebrand's data further indicate that during terrestrial walking the hands of some gorillas are in contact with the substratum for longer durations than the feet [p. 125].

The fundamental patterns of stance and stride in *Pan gorilla* are closely similar to those of *Pan troglodytes*, but the former species frequently exhibits greater squaring and jutting forward of the shoulder than the latter. In adult gorillas this may be due, in part, to the more massive development of the deltoid muscles, but perhaps the major factor contributing to this effect is medial rotation of the shoulder and elbow joints such that the hands are consistently placed approximately perpendicular to the line of progression.

In gorillas, as in chimpanzees, the primary propulsive force for quadrupedal terrestrial locomotion appears to be provided by the hindlimbs, with strong supplementary force from the retractor muscles of the shoulder complex. During quadrupedal stance and progression, the knee joints are persistently flexed while the elbow joints are fully extended.

The feet of gorillas are basically plantigrade and their hands are placed in knuckle-walking postures on flat substrates, including stout horizontal branches. The pattern of knuckle-walking in gorillas is very similar to that of chimpanzees except that in the former apes the four fingers of a hand appear to be more uniformly involved in locomotor support. By contrast, in chimpanzees the index and little fingers sometimes are carried free of the ground (at least for short distances) with no apparent impairment of gait [TUTTLE, 1967].

Free-ranging eastern mountain gorillas rarely engage in bipedal locomotion and stance [BINGHAM, 1932, p. 47; SCHALLER, 1963, p. 82]. SCHALLER observed brief bouts of bipedalism in gorillas only in special contexts such as object transport [p. 83] and as part of precopulatory [p. 281] and chest-

beating [p. 222] displays. Gorillas assume a flexed hip, bent-knee, plantigrade posture when standing and moving bipedally.

Although gorillas collect the majority of a day's fare on the ground, in localities where trees are strong enough to support their considerable weight they climb readily for supplementary foods, and to rest, play, and nest [SCHALLER, p. 81; BINGHAM, 1932, p. 60; DONISTHORPE, 1958, p. 213]. Gorillas cautiously ascend trees by climbing step-wise up the trunk and utilizing opportunistically existent irregularities in the bark, branches, and other potential supports for hand and footholds [SCHALLER, p. 83].

SCHALLER [p. 83] describes the climbing activities of gorillas as 'extremely cautious, in sharp contrast to the chimpanzee'. SCHALLER further notes that gorillas rarely jump from branch to branch or move rapidly in trees and that 'their feet are incapable of holding onto branches securely' [p. 83]. However, if an animal slips it may prevent itself from falling to the ground with firm handholds [SCHALLER, p. 83].

Although gorillas, particularly young individuals, may occasionally hang beneath a branch from the hands alone or move from one branch to another by arm-swinging, they do not traverse the canopy with a series of arm-swinging strides. SCHALLER [p. 84] considers the notion that great apes are 'full brachiators' to be controverted by behavioral evidence and further asserts that all of the large-bodied apes 'are essentially quadrupedal climbers'.

Gorillas descend trees feet first. If the tree possesses protrusions suitable for hand and footholds, the movements of descent are basically the reverse of those used for ascension. If, on the other hand, the tree lacks suitable potential grips, a gorilla may slide hand over hand down the smooth trunk while using the soles of the feet as brakes [SCHALLER, p. 84; DONISTHORPE, 1958, p. 213].

Gorillas rarely jump in trees and the distance that they can traverse thus have not been observed to exceed ten feet [SCHALLER, p. 84]. Unlike chimpanzees, gorillas refuse to jump from tall trees. When they drop to the ground from low branches, even when frightened by an intruder, they frequently hang 'first by both arms, then only by one arm as they scan the vegetation below for several seconds before finally releasing their hold' [SCHALLER, p. 85]. Gorillas also jump occasionally from atop a low branch [DONISTHORPE, 1958, p. 213].

SCHALLER [p. 85] and DONISTHORPE [p. 213] describe gorillas landing either on all fours or on their hindlimbs in a manner that allows them to quickly become quadrupedal. It is not clear from SCHALLER's description that the hindlimbs consistently receive the initial shock of landing in gorillas as

appears to be the case in chimpanzees that jump on the ground [REYNOLDS, 1965, p. 62].

Orangutans are the only great apes that habitually traverse the canopy when moving from one locality to another. Orangutans generally move quadrupedally atop large branches with a slow deliberate mein, but they may also move at considerable speeds if a suitable sequence of supports is available [WALLACE, 1890, p. 40]. They change to suspensory postures in the periphery of trees where strong supporting limbs are infrequent or absent. In moving between closely juxtaposed trees, orangutans carefully pull in small branches from the adjacent tree until a large branch or a number of small branches can be firmly grasped. Then its hand and footholds on the base tree are transferred to the new supports [WALLACE, 1890; SCHALLER, 1961; DAVENPORT, 1967].

Orangutans may suspend themselves by all combinations of hand and footholds when transferring their prodigious bulk from one tree to the next or attempting to reach a desired food object. During most bouts of suspensory posturing and locomotion, orangutans grasp the foliage with three or four cheiridia. Arm-swinging along a branch and between closely juxtaposed branches is infrequent and appears, in great part, to depend on the availability of an especially suitable superstratum [WALLACE, 1890, p. 31; SCHALLER, 1961; DAVENPORT, 1967].

Orangutans have not been observed to 'jump' in the manner described for chimpanzees. However, DAVENPORT [1967, p. 251] has described two 'dives' wherein an animal arose from a quadrupedal posture on top of a horizontal limb and 'either lunged or fell forward' while holding on with its feet alone. At the end of the 'dive' the animal hung upside down beneath the branch for 'approximately one minute' and then recovered itself and moved back into the base tree. These 'dives' appeared to be related to threat displays and were not associated with transfers from one tree to another. Davenport, however, described an energetic mode of arboreal transfer as follows: '... holding onto a limber branch and setting it in pendulous motion with vigorous swings of the body until an excursion of the limb carried the animal within reach of the top or other limbs of the adjacent tree' [p. 252]. After achieving an initial hold on the new support, the remainder of the climb from the base tree was executed cautiously.

When induced to progress on the ground, orangutans, like the African apes, exhibit symmetrical gaits of 'trot' and 'diagonal-sequence, diagonal-couplet' varieties [HILDEBRAND, 1967].

One of the most notable differences between the patterns of terrestrial

stance and progression in *Pongo* and *Pan* is to be observed in modes of hand posturing (fig.4). Whereas the African apes are consistently knuckle-walking, orangutans have not been seen to support themselves exclusively on the middle phalanges of digits II-V. Instead, *Pongo* exhibit a variety of 'fist-walking' and 'palmigrade' postures [TUTTLE, 1967, 1969].

WALLACE [1890, p. 45] described an orangutan walking atop large branches 'on his knuckles<sup>2</sup>, not on the palm of the hand, as we should do.' Thus in orangutans flexed finger postures are not strictly an adjustment to an unfamiliar substratum. It is probable that some orangutans utilize fist-walking postures on large branches much as the African apes knuckle-walk in trees, but that they too change to palmigrade prehensile postures on branches of smaller diameter.

On the ground orangutans generally walk on the lateral aspects of their feet with toes markedly flexed (fig.4). In some individuals, particularly those that are accustomed to walking on cage floors, the toes may be extended, but the permanent plantar curvature of the phalanges and metatarsals and the flexion set of the digital joints prohibit them from being apposed flatly against the ground. Further, the configuration of the ankle joints is such that the feet are permanently inverted and this again limits the extent to which the soles can be apposed to the substratum.

During a stride the diminutive halluces of some individuals may remain free of the ground while in others they may touch the substrate but without proffering much support to the foot.

Orangutans maintain their elbows in full extension and also demonstrate a remarkable potential to extend the knee and hip joints at the end of a quadrupedal stride. The capacity to extend the hip and knee joints such that the hindlimb forms a nearly straight supporting column is exhibited also in some animals that engage in facultative bipedalism.

In summary, free-ranging *Pan troglodytes*, *Pan gorilla*, and *Pongo pygmaeus* are basically semierect quadrupedal climbers in trees and the former two species are plantigrade, knuckle-walking quadrupeds on the ground. Although all great apes have the morphological capacity to engage in prehensile suspensory locomotion only orangutans and, to a lesser extent, chimpanzees among adult large-bodied apes utilize this potential in play and display, to transfer from tree to tree and to obtain foods in small branch areas of the canopy.

2 The animal observed by WALLACE was probably walking on its *proximal* phalanges since many early observers did not distinguish the unique flexed-finger posture of the African apes from those of orangutans.





*Fig. 4. Cheiridial posturing in Pongo pygmaeus.*

- a. Subadult orangutan with left hand in modified palmigrade posture. Note that hand is positioned outward, perpendicular to the line of forward progression. The toes are flexed and the pedal load is borne mainly by the lateral border of the sole.
- b. Subadult orangutan in quadrupedal fist-walking stance. The dorsal aspects of the proximal phalanges are in contact with the substratum. The toes are flexed and the pedal load is borne as in animal (a).



- c. Quadrupedal stance in juvenile orangutan. The proximal phalanges are the major contact points in the hands. Note marked supination of left foot such that only the lateral border of the sole and fifth digit contact the ground.
- d. Anterior view of a palmigrade posture in the right hand of an adult orangutan. Note that load appears to be borne mainly by posterior aspect of the palm. The curvature of phalanges and permanent flexion set of the metacarpophalangeal and interphalangeal joints prevent the fingers from lying flat against the substratum.
- e. Prehensile manual grip of an adult orangutan on a superstratum.
- f. Posterior view of a palmigrade posture in the right hand of an adult orangutan. The hand was being raised as picture was taken. Note also the rather marked plantigrade posture of the right foot.
- g. Suspensory prehensile grip in the left foot of an adult orangutan (photographs by I. BERNSTEIN and F. KIERNAN, Yerkes Regional Primate Research Center).

## III. FORAGING AND MANIPULATORY MODES

In eastern Africa, chimpanzees have been observed to spend 50 to 75% of diurnal hours foraging, feeding, and resting in trees [REYNOLDS and REYNOLDS, 1965, p. 383; GOODALL, 1965, p. 437]. The major constituents of chimpanzee fare are arboreal fruits. Chimpanzees rarely feed intensively on the ground though while foraging between trees they may stop briefly to eat parts of ground plants and fallen fruits. In some localities they gather termites seasonally [GOODALL, 1963, pp. 40 and 43].

NISSEN [1931, p. 65] estimated that Guinean chimpanzees spend between three and six hours in feeding. GOODALL [1963, p. 39] observed that Tanzanian chimpanzees spend between six and seven hours per day in active feeding. REYNOLDS and REYNOLDS [1965, p. 381] stated that 'in order to subsist on a predominantly fruit diet (Ugandan chimpanzees) must spend from six to eight hours per day feeding or foraging', but their observations of feeding behavior apparently were too fragmentary to proffer more reliable quantitative estimates.

Chimpanzees, like most other primates, are fundamentally eclectic hand-to-mouth feeders. Their long arms and prehensile feet are particularly well suited to gather fruits from the vantage point of the larger limbs in trees. They sit, squat, stand, or recline on a limb and, while holding on to it or a nearby branch with one hand, reach out to collect fruits, leaves, buds and other foods [NISSEN, 1931, p. 67; GOODALL, 1963, p. 41]. Small fruits may be plucked selectively and carried to mouth. Or a twig bearing the entire cluster of fruits may be broken off and ingested, often following further manipulation with the hands or lips. Large fruits generally are picked individually by hand and may be pounded against the trunk of a tree in order to crack a hard rind [GOODALL, p. 40].

Chimpanzees frequently use their feet to secure their positions on a base branch, to hold a food bearing limb while its fruits are collected directly by hand or lips, and to break off twigs laden with fruit. But the feet are not used like hands to convey foods to mouth [NISSEN, p. 67; GOODALL, p. 40].

Although chimpanzees commonly forage and feed from relatively secure vantage points atop stout limbs, they also climb dauntlessly into the peripheral foliage of tall trees and the tops of saplings in order to obtain desired foods [REYNOLDS, 1965, pp. 49 and 59]. Chimpanzees use suspensory postures while feeding in the terminal branches of trees. The animals hang freely by one arm while reaching for fruits with the other, and they apparent-

ly prefer to grasp additional branches (if present) with the feet [GOODALL, 1965, p. 440].

The manipulatory capabilities of *Pan troglodytes*, *Pan gorilla*, and *Pongo pygmaeus* have been determined by film analyses of captive animals handling food objects ranging in size from grains of rice and corn to coconuts in the husk [TUTTLE, 1965a and b and 1969].

In general, regardless of the size of the food object that the animals attempt to secure, the first digital ray is moved *as a unit* at the carpometacarpal joint. Notable flexion of the interphalangeal and metacarpophalangeal joints is negligible or nil under most circumstances. However, slight flexion (beyond the permanent flexion set) of the distal phalanx may be observed. For example, one chimpanzee flexed its distal phalanges when it plunged its thumbs into the center of a grapefruit and broke it open.

Chimpanzees are proficient in picking up small objects such as rice and corn from flat surfaces. Their performance of this task evidences considerable tactile sensitivity and refined motor control of the digits. They usually oppose the pulp of the thumb to the lateral aspect of the index finger at a point somewhere between the proximal and distal interphalangeal joints (fig. 5). Occasionally by acutely flexing the index finger individuals oppose the pollical distal pad to the lateral aspect or tip of the distal pad of digit II. Pulp-to-pulp prehensile patterns also may be observed when chimpanzees hold grapes or larger food objects and when they pinch sizable folds of skin during grooming.

When chimpanzees grasp round or cylindrical objects such as oranges and carrots the thumb is commonly opposed to the medial four digits. When they manipulate large spherical objects, such as grapefruit and coconuts in the husk, the thumb is usually widely abducted and flexed in opposition to the fingers.

The adaptive value of refined manipulatory skills in chimpanzees is exhibited not only in their arboreal locomotor and subsistence activities but also in nesting and grooming behaviors. Chimpanzees regularly build nests in the middle and upper levels of trees. Each animal, except small infants, commonly constructs a new nest every evening in a non-food tree. Nests are rarely reused. On occasions of reuse the occupants evidently execute some reconstructive efforts [NISSEN, pp. 50-51; GOODALL, 1963, p. 460 and 1965, p. 447]. GOODALL [1963, p. 460] associates the making of a new nest each evening with the fact that chimpanzees follow no regular routes in daily foraging.

Chimpanzees can build nests quickly. Most animals complete the basic



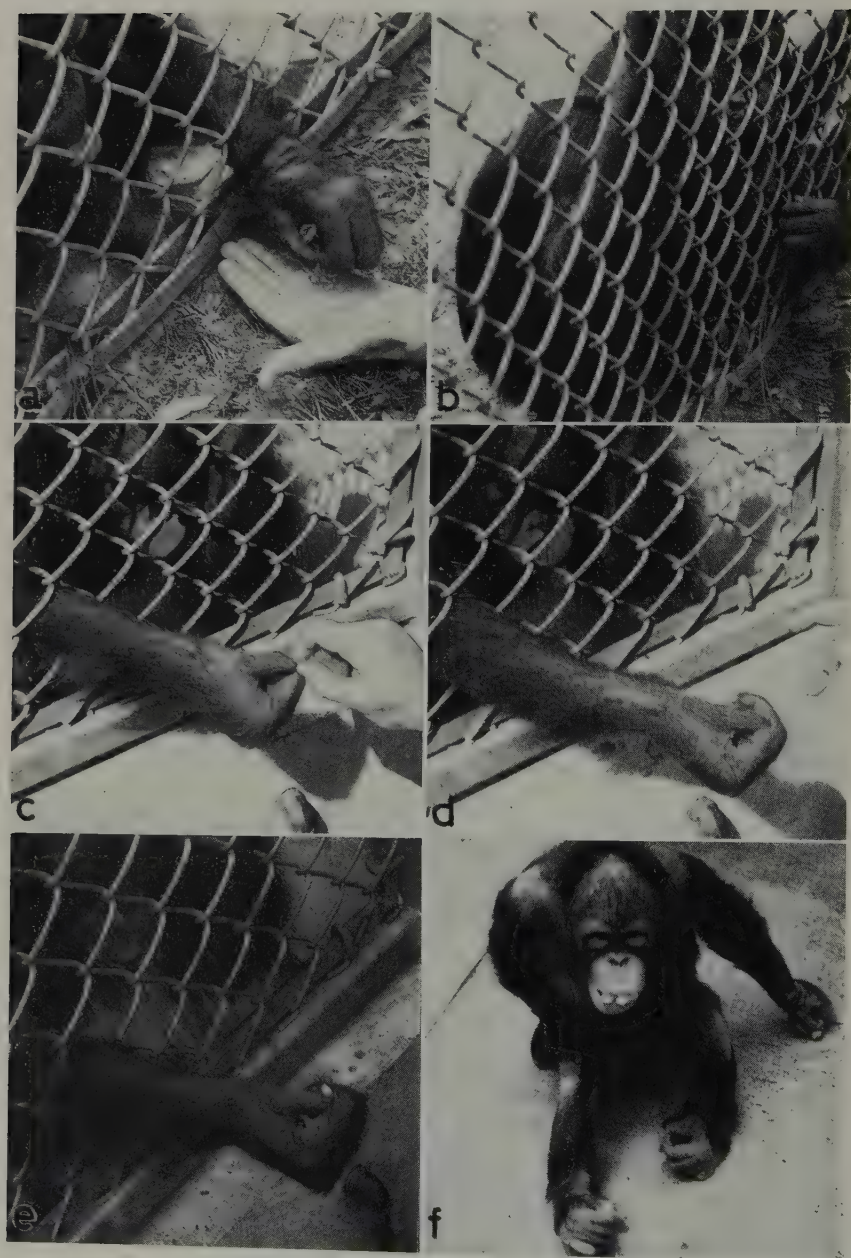


Fig. 5. Manipulation of small objects by *Pan troglodytes* and *Pongo pygmaeus*.

fabrication of a night nest in one to five minutes [NISSEN, 1931, p. 43; BOLWIG, 1959, p. 291; GOODALL, 1963, p. 460; REYNOLDS, 1965, p. 128].

Nesting chimpanzees generally choose a stout branch, crotch, or set of closely juxtaposed limbs. While standing on this foundation, they bend smaller branches in toward the center. The hands are prominent in selecting and drawing in branches while the feet hold them in place. After four to six primary crosspieces have been secured in this manner, from six to ten additional branches are bent into the center of the nest. Chimpanzees often interweave the crosspieces, sometimes in quite complicated patterns, using both hands and feet. Completion of the nest involves the selection and placement of small leafy twigs on the platform of branches [GOODALL, 1963, p. 460; BOLWIG, 1959, p. 290; REYNOLDS, 1965, p. 128; NISSEN, 1931, p. 43].

GOODALL [1963, p. 461] found no evidence that chimpanzees transport materials to the nesting tree from other localities. NISSEN [1931, p. 44], on the other hand, reported that a few loose twigs from one non-food tree had been utilized in the construction of a nest in another.

In night nesting, chimpanzees recline on their backs or sides. Normally they do not hold on to branches with hands or feet [GOODALL, 1965, p. 449]. By contrast, in daytime resting, chimpanzees often lie along a limb and grasp nearby branches, generally overhead, with hand or foot [NISSEN, 1931, p. 31].

During the rainy season in Tanzania some chimpanzees build nests in trees for daytime resting. But these nests often are not constructed as elaborately as night nests and they are built only sporadically by a minority of individuals [GOODALL, 1963, p. 465].

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- a. Juvenile chimpanzee picking up a single grain of rice between the pulp of the thumb and the side of the distal interphalangeal joint of the index finger.
  - b. Juvenile chimpanzee holding a kernel of maize between the pulp of the thumb and the side of the proximal phalanx of the index finger.
  - c. Juvenile orangutan and human investigator holding the same grain of rice. Note pulp-to-pulp pattern of opposition in the human hand.
  - d. Animal (c) holding single grain of rice between the pulp of the thumb and the lateral aspect of the proximal interphalangeal joint immediately after the object is released by human observer.
  - e. Juvenile orangutan holding a kernel of maize between the pulp of the thumb and the lateral base of the middle phalanx of the index finger.
  - f. Juvenile orangutan holding an unshelled peanut between the pulp of the pollex and the lateral aspect of the proximal phalanx of digit II (photographs by I. BERNSTEIN, Yerkes Regional Primate Research Center).

KORTLANDT [1962], REYNOLDS and REYNOLDS [1965, p. 386], NISSEN [1931, p. 31], and BOLWIG [1959] have noted in their study areas constructions on the ground that may be attributed to *Pan troglodytes*. However, nesting on the ground may be considered extremely rare in the species. NISSEN [p. 31] emphasized the crude craftsmanship of the 'day-beds' in Guinea and the fact that 'they have nothing in common with nests used at night except that both are used as beds in the broadest sense of the word'. REYNOLDS and REYNOLDS [1965] found only two 'ground nests', both of which were comparable to those described by NISSEN. KORTLANDT is the only observer who has reported that chimpanzees may utilize ground nests at night but he has not presented systematic data on the distribution and frequency of this behavior [KORTLANDT, 1962; REYNOLDS and REYNOLDS, 1965, p. 386].

Chimpanzees frequently engage in auto- and allogrooming during daytime rest periods in trees and on the ground. The frequency of grooming appears to be related to the availability of foods and concomitantly the duration of foraging and feeding bouts. In periods of plenty, chimpanzees probably have more 'free time' to groom [REYNOLDS and REYNOLDS, 1965, p. 417].

The groomer parts the hair in the grooming area with the backs of the fingers or side of the thumb [LAWICK-GOODALL, 1967, p. 324]. Captive chimpanzees sometimes pinch folds of skin between the thumb and forefinger or between the tips of the index fingers [TUTTLE, 1965a]. If a piece of scurf or an extraneous particle is discovered thus, it may be removed directly with the lips or between the thumb and index finger [GOODALL, 1965, p. 446].

Eastern mountain gorillas forage preferentially in secondary forest, bamboo forest, and open river valleys that are heavily overgrown with tree ferns, vines and herbs [SCHALLER, 1963, pp. 45 and 54]. They spend about 80 to 90% of their waking hours on the ground [SCHALLER, p. 82]. Two major periods of feeding typify the activity cycle of gorillas; one shortly after rising in the morning and approximately two hours in length and a second, more prolonged bout following the midday rest and lasting until dusk [SCHALLER, pp. 139 and 146].

Gorillas generally sit on their haunches and reach for food in all directions. Feeding may begin thus before they leave their nests in the morning [SCHALLER, pp. 154-155]. Most foods are collected entirely by hand. Eastern mountain gorillas, unlike chimpanzees, do not use their feet commonly to secure branches or directly to collect foods. Frequently the hands select and hold a food object while it is torn free from the base plant with the teeth. Since gorillas feed primarily on bamboo, bark, vines and other fibrous vege-



table matter, the teeth probably are used by them more prominently for tearing, shredding, and otherwise collecting and preparing foods than they are in predominantly frugivorous chimpanzees [BINGHAM, 1932, pp. 23-25; SCHALLER, 1963, p. 156].

Gorillas not only engage in gross manipulations of tough, resilient parts of plants but also collect small tender foods with refined manipulatory patterns. For example, they may selectively pick ferns, leaves, blossoms and small fruits between thumb and index finger [SCHALLER, pp. 158-163]. Observations of captive gorillas demonstrate that they have a predilection for grasping small objects between the pulp of the thumb and side of the index finger in a manner reminiscent of chimpanzees. But when offered an object with the diameter of a large grape or cigar they may grasp it between the distal pads of the pollex and index finger [TUTTLE, 1965, 1969]. Spherical and cylindrical objects of moderate size and larger usually are grasped with the pollex actively gripping the surface in opposition to digits II-V.

Gorillas nest and rest on the ground more often than chimpanzees. In areas where *Pan gorilla* are sympatric with *Pan troglodytes* the vertical distributions of their nests rarely overlap since the former tend to remain on or near the ground whereas the latter sleep at higher levels in trees [SCHALLER, 1963, p. 181; BOLWIG, 1959; DONISTHORPE, 1958].

Gorillas nests are generally simpler in construction than those of chimpanzees. The crosspieces are infrequently interlaced and the bed of the nest is rarely padded with supplementary leafy twigs [SCHALLER, p. 187]. This is probably in part concordant with the terrestrial nesting practice of gorillas and reflects little on their relative manipulatory abilities. Recall that chimpanzee ground nests also demonstrate less complicated workmanship than their night nests. Further the large size of gorillas may confine their tree nesting mainly to crotches and large limbs [SCHALLER, p. 191]. Consequently there is little opportunity or need to interweave branches in order to provide a substantial platform.

SCHALLER observed that about five percent only of gorillas build nests during the midday rest instead of simply reclining or sitting on a low branch, crotch, or the ground. The day nests vary in construction from a few handfuls of herbs to elaborate platforms in trees [SCHALLER, p. 170].

Gorillas construct night nests far more frequently than day nests. Nests are rarely if ever reused [SCHALLER, p. 171]. Whether they are located in trees or on the ground apparently depends, to a great extent, on the type of vegetation available in the area. But there is also some suggestion that re-



gional differences in tree nesting may be due to habit as well [SCHALLER, 1963, pp. 180-181].

Data collected by SCHALLER [1965, p. 359] demonstrate that gorilla nests are located on the ground approximately 97 % of time in *Hegenia* woodland, 45 % in mountain woodland and bamboo forest, 54 % in mountain rain forest, and 22 % in lowland rain forest. Gorillas rarely nest more than ten feet above ground except in lowland rain forest where they may reach heights above thirty feet [SCHALLER, 1965, p. 359 and 1963, pp. 180-181]. Juveniles, subadults and adult females may be responsible for the majority of nests in the less secure segments of trees [BINGHAM, 1932, p. 32; DONISTHORPE, 1958].

Gorillas may construct their nests in a few seconds or periods up to five minutes or longer according to the location of the nesting site (particularly whether in trees or on the ground), intensity of building activity, and the care taken in fabrication [SCHALLER, 1963, p. 194]. Each gorilla builds its own nest except infants that sleep with their mothers and juveniles that occasionally sleep together [SCHALLER, pp. 184-185].

Gorillas sleep either on their sides with knees drawn up close to the body and one or both arms folded over the chest, or in quasi-prone postures with legs and arms tucked under the body [SCHALLER, p. 196]. Thus, gorillas like chimpanzees generally do not hold on to nearby branches while sleeping. Further, gorillas may use their feet less frequently than chimpanzees in manipulating nest materials since they often sit on the ground or secure region of a tree and draw in nearby vegetation in a manner reminiscent of their basic feeding posture [SCHALLER, p. 187]. Mountain gorillas rarely transport nesting materials, the maximum distance being fifteen feet [SCHALLER, p. 198; BINGHAM, 1932, p. 35].

SCHALLER [1963, p. 82] estimated that 'gorillas spend roughly one-third of the day in a vertical position on their hindlimbs with their hands freed for such tasks as feeding and grooming'. Most grooming occurs during the midday rest period [SCHALLER, p. 205]. Grooming activities, especially allogrooming, appear to be less frequent in mountain gorillas than in chimpanzees according to the observations of SCHALLER [1963] and GOODALL [1965] and LAWICK-GOODALL [1967], respectively. In gorillas, bouts of auto- and allogrooming are brief, rarely exceeding ten minutes, and fundamentally subserve hygienic functions [SCHALLER, p. 248]. By contrast, in chimpanzees allogrooming sessions may last as long as two hours [GOODALL, 1965, p. 470]. Although the greater frequency of grooming behavior in the chimpanzees observed by GOODALL may be explained in part by the fact that the

animals are provisioned and thus may have more time free from basic subsistence activities, her conclusion that 'mutual grooming ... plays an important part in the social life of the chimpanzee' [1965, p. 469] is probably correct. Further observations on gorillas may be necessary to ascertain the subtleties of the adaptive values of their grooming patterns.

Autogrooming gorillas concentrate on their arms, shoulders, chest, abdomen, and legs. They may groom an arm or shoulder with the contralateral hand alone, or in addition, hold back hair in the region with chin or mouth. Other regions are autogroomed with both hands; one hand holds back the hair while the other hand contacts the skin. The rump, back, and head are either scratched or presented for allogrooming. Gorillas generally allogroom with both hands in the manner described for two-handed autogrooming [SCHALLER, p. 205].

An area of exposed skin may be picked with the nail of a flexed index finger. This evidences refined independent control of the forefinger. Pieces of scurf and other particles are picked up between thumb and index finger or directly with the lips. In the former instance the object may be manipulated finely and observed carefully before ingestion [SCHALLER, p. 205].

Orangutans forage and feed predominantly in primary equatorial rain forests of mixed swamp forest type [SCHALLER, 1961, p. 76; WALLACE, 1890, pp. 44-45]. DAVENPORT [1967] observed that individual orangutans may spend from 24 to 60% of waking hours in feeding. Sporadic observations by SCHALLER [1961], HARRISSON [1962, pp. 68-71 and 77-78], and WALLACE [1890, p. 46] indicate that orangutans are primarily frugivorous. DAVENPORT reported that in Sabah orangutans fed on leaves and shoots 90% of time [1967, p. 253]. Variations in these observations may be correlated with the differential availability of seasonal fruits such as durian and the fact that there is little overlap in the times or areas in which observations have been conducted.

Extremely mobile shoulder and hip joints, extensible knee and elbow joints, and highly prehensile hands and feet, enable orangutans to assume a wide variety of standing and suspensory postures while foraging and feeding (fig. 6). Some of these postures may be illustrated by the following quotations:

'one of them stood on a high branch, with one hand interlocked higher up, the other hand taking one spray after the other that sprouted outwards from the main bough, turning them inside towards his face, to chew the young tips' [HARRISSON, 1962, p. 68]. 'He stood erect on twisted branches, legs spread apart, holding on to a vine' [HARRISSON, 1962, p. 68]. 'He ... swung back to hang on one arm, hugging the (durian) fruit between hand



*Fig. 6.* Suspensory postures in *Pongo pygmaeus*.

- a. Juvenile orangutan hanging from bars in cage roof by both hands and feet. Note extreme extensibility of knee and flexibility of hip joints. The right foot is in front of the right hand and the left hand is in front of the left foot.
- b. Juvenile orangutan hanging by both hands and the left foot.

and feet in close embrace' [HARRISSON, 1962, p. 78 and illustrated in *frontpiece*]. 'Hanging by one arm and foot while reaching for food is not unusual, and once a subadult hung two to three seconds by its feet alone' [SCHALLER, 1961, p. 78; also see illustrations in EIMERL and DEVORE, 1965, p. 80].

Despite the seeming disproportionate length of the fingers relative to the thumb, orangutans are adept in collecting selectively and manipulating foods and other objects. For instance, SCHALLER [1961, p. 79] observed them plucking small olive-sized fruits 'in a row ... between thumb and index finger.'

Larger foods may be collected with hands and teeth. SCHALLER [1961, p. 79] described an animal tapping the back of a durian fruit with one hand while grabbing it by mouth and detaching it with a backward jerk of the head. Orangutans hold durians with hands alone or more rarely with hands and feet as they bite through the tough rind to get at the seeds and pulp. HARRISSON [1962, pp. 77-78] provided the following description of orangutans collecting durian fruits: 'They bit off the stem from its branch, supporting the large fruit below with their hands. They then moved farther away carrying the fruit between their teeth.' ... 'Finally, they wrenched the shells open, tearing and splitting with teeth and hands.'

DAVENPORT [1967, p. 254] has summarized his observations of orangutan feeding techniques as follows: 'The animals either bit off leaves and fruit directly with the mouth, or about as often, brought them to the mouth by hand. In the latter case a branch might be bent to the mouth or an object plucked off and transferred to the mouth by holding the thumb opposed to the outside surface of the forefinger.'

Thus orangutans like gorillas appear to utilize their teeth to collect foods more frequently than do chimpanzees. The extent to which this is due to a lesser degree of manipulatory capability in orangutans or merely the consistency of the vegetation, or both cannot be determined from present sporadic observations of free-ranging animals.

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- c. Subadult orangutan hanging headlong by both feet and the left hand. Note that whereas the left foot is markedly supinated the right foot is markedly pronated on the same bar. The suspensory hand is notably supinated.
  - d. Juvenile orangutan hanging headlong by its feet alone. This posture is assumed by releasing the hands and rocking backwards from a position similar to that of animal (a) (photographs by I. BERNSTEIN and F. KIERNAN, Yerkes Regional Primate Research Center).



Studies on the manipulatory capacities of captive orangutans suggest that they may be somewhat less adept than chimpanzees in gripping very small and large spherical objects with the thumb [TUTTLE, 1969]. However, observations by TUTTLE [1965a and b and 1969] on a sizable series of orangutans and chimpanzees do not support the conclusion of NAPIER [1960, p. 653] that 'while the thumb at least contributes – though ineffectively – to the precision grip it plays little or no part in the power grip which is produced solely by flexion of the fingers in both chimpanzees and orangs.'

Captive orangutans and chimpanzees often utilized the thumb quite effectively in picking up grains of rice, corn and raisins from flat surfaces. Further, apples and oranges, though mainly supported with the fingers, were manipulated by orangutans into a position suitable for grasping by the thumb which appeared also to be active in the final grip. Orangutans frequently grasped carrots with a 'power grip', reminiscent of a man grasping a handle, when they were permitted to manipulate the object themselves into a position to be collected. Large spherical objects, such as grapefruit and coconuts in the husk, were held mainly by the fingers with the thumb slipping ineffectually along the surface.

In addition to observations by TUTTLE (fig. 5), illustrations by HARRISSON [1962, plates facing pp. 49, 80, 81, 128 and 161] of relatively unrestrained orangutans manipulating objects and climbing demonstrate that the thumb frequently is involved in gripping small and moderate sized objects. NAPIER conducted his observations on three young animals that were reaching through narrow apertures in a cage. This may in part explain the inadequacy of his generalization.

Orangutans nest in trees at night, generally at heights above 20 ft [WALLACE, 1890, p. 45; SCHALLER, 1961, p. 80]. They often construct nests in food trees and occasionally eat leaves surrounding the nest while lying in it [DAVENPORT, 1967, p. 255]. In general each adult orangutan builds a new nest every evening. HARRISSON [1962, pp. 77–78] observed two juveniles sleeping in the same nest at dawn and during daytime rest. Nests probably are not reused for night nesting, but orangutans often take daytime rests in nests that were used on the previous evening [DAVENPORT, 1967, p. 255; HARRISSON, 1962, p. 78].

SCHALLER [1961, p. 80] found orangutan nests in major crotches, in forks at the extremities of large limbs, along horizontal branches, and in the crowns of single or closely juxtaposed trees. The builder generally stands quadrupedally on the foundation and draws in three to nine smaller bran-

ches by hand. The crosspieces are held in place by the feet or rump and are not interlaced [SCHALLER, 1961, p. 80; DAVENPORT, 1967, pp. 255–256]. HARRISSON [1962, pp. 71 and 78] described orangutans packing down crosspieces with strong, regular movements of the fists while turning slowly round in a circle.

Detailed examinations of orangutan nests by SCHALLER [1961, p. 80] revealed that 'most nests have a lining of small twigs about one foot in length which the animal breaks off around the nest.' Further, SCHALLER [1961] and HARRISSON [1962, pp. 70–71] reported that orangutans occasionally transported additional branches from areas that were some distance from the nest. For instance, HARRISSON observed an orangutan making several trips to a partially constructed nest with branches and a durian fruit in its teeth. Each time, the supplementary branch was carefully incorporated into the platform of the nest. DAVENPORT [1967], by contrast, never observed transport of nest materials.

Some orangutan nests are unique compared to those of the African apes in possessing an overhead shelter. DAVENPORT observed the fabrication of these shelters during heavy rains. He described the pattern of construction as basically similar to that used for the platform of the nest, 'except that they were constructed from a position below the shelter and the limbs were bent and jammed into place in other limbs instead of being held down by the feet' [1967, p. 256].

DAVENPORT [1967, p. 256] stated that 'adult animals characteristically slept on the side or supine. The role played by the hands and feet in securing orangutans in nests is not clear from available field reports. HARRISSON [1962, p. 77] described one sleeping posture as follows: '... feet folded under the body. One hand was tucked under the shoulder, the other gripped a branch that stuck out from the nest.' Accounts of early naturalists, summarized by YERKES and YERKES [1929, pp. 119–122], attribute different degrees of importance to cheiridial prehensility during sleep. For example, SCHLEGEL and MULLER [1839–44, p. 15] described the 'characteristic sleeping attitude' of orangutans as being 'on the back or side with the legs drawn close to the body while the hands either support the head or are folded across the body' [paraphrased translation by YERKES and YERKES, 1929, p. 119]. By contrast, HORNADAY [1879, pp. 445–446 and 1885, pp. 393–394] and SELFORD [1916, pp. 3–4] reported that orangutans tightly grip large branches with hands and feet while lying on their backs.

In summary, although chimpanzees are primarily arboreal in feeding and nesting habits, they generally forage from one site to another on the ground.

Gorillas are basically terrestrial in foraging, feeding, and to a great extent also in nesting behaviors. Orangutans are arboreal in these behaviors.

The great apes possess refined capacities to manipulate objects of diverse sizes. These skills are of special value in selective feeding, grooming and nesting.

In chimpanzees, both hands and feet are prominent in collecting foods. The hands select and convey foods to mouth while the feet secure the position of the animal or the food bearing branch. Occasionally foods may be collected by foot, but these are subsequently conveyed to mouth by hand. Orangutans, like chimpanzees, use both hands and feet in subsistence activities, but in gorillas the feet are less prominent in food gathering.

Similarly, due to the arboreal nesting practices of chimpanzees and orangutans, their feet are utilized more for prehensile functions than those of gorillas.

Gorillas and orangutans appear to use their teeth more frequently than do chimpanzees during food gathering, but this does not reflect on the relative manipulatory skills in the hands of the three species.

#### IV. MORPHOLOGICAL AND FUNCTIONAL ASPECTS OF CHIMPANZEE HANDS

In chimpanzee hands, morphological correlates with the functional compromises that are exhibited between support and locomotion on the ground versus in trees and between these locomotive activities, on the one hand, and manipulatory behaviors, on the other, may be revealed by considering together results from several anatomical methods.

Two fundamental locomotor modes exert the most prominent stresses on the chimpanzee hand. Firstly, in knuckle-walking postures the hand is consistently subjected to compressive forces that challenge in particular the integrity of the wrist and second to fifth metacarpophalangeal joints. Secondly, suspensory postures, wherein most of the weight of the animal is supported beneath a superstratum, subject the hand to sizable tensile forces.

The behavioral data that are summarized above indicate that with regard to both duration and vigor, the frequency of knuckle-walking exceeds considerably the incidence of suspensory posturing in chimpanzees. During the remainder of time, the forelimbs generally are free from support functions and either are utilized for manipulation or remain at rest.

*A. Morphological Bases of Knuckle-Walking*

The maintenance of integrity of the wrist joint in static knuckle-walking postures is probably effected primarily by intrinsic structures. The carpus, metacarpus, and radius are aligned to form a supporting column. There is a notable absence of dorsal displacement in the carpus, and, when viewed externally, the dorsal aspect of the wrist is curved slightly convexly (fig. 1).

The carpal bones fit closely with one another and with the metacarpus and radius when the wrist is passively moved into a position of dorsiflexion or abduction. For example, there is a prominent ridge between the distal and medial surfaces of the scaphoid bone that fits into a constriction on the lateral aspect of the neck of the capitate bone [SCHREIBER, 1936; TUTTLE, 1965a and 1967]. Further the articulations between the distal surface of the scaphoid bone and the proximal surfaces of the trapezium and trapezoid bones are of the plane variety and therefore permit only limited amounts of gliding. Similarly, the second to fifth carpometacarpal joints are generally planar.

The dorsodistal extremity of the radius possesses a prominent ridge that is closely related to the ridge on the scaphoid bone formed at the border of its proximal and distal articular surface.

The ligaments in the dorsal capsule of the wrist joint are transversely directed and are not as well developed as those in the lateral, medial and palmar aspects of the articular capsule. The palmar aspect of the wrist in particular is covered by heavy radiocarpal, radial and ulnar collateral, intercarpal, and carpometacarpal ligaments that generally are disposed vertically and obliquely (fig. 7).

Thus in the chimpanzee wrist, features developed to withstand the compressive components of forces that are incurred in static knuckle-walking are located on the dorsal aspect whereas structures suited to take tensile components of these forces (viz. ligaments) are situated on the palmar aspect. This arrangement is reminiscent of the basic mechanism that maintains the longitudinal arch of the human foot during static posturing [MORTON, 1935, pp. 60-62].

In dynamic knuckle-walking the maintenance of integrity of the wrist joint is probably effected prominently by extrinsic features, particularly the well developed muscles that cross the palmar aspect of the carpus.

In chimpanzees the proper flexor muscles of the wrist (viz. flexors carpi radialis and ulnaris and palmaris longus) are especially well developed compared to those of man and the orangutan [TUTTLE, 1969 and in press b]. Wrist flexion through notable excursions is not a prominent component in the





Fig. 7. Development of wrist ligaments in *Pan troglodytes*.

- a. Fresh preparation of lateral aspect of left wrist. A well developed radiocarpal ligament (c) attaches to the styloid process of the radius (R) and the lunate and capitate bones. As the hand moves into dorsiflexion (arrow) the radiocarpal ligament becomes taut and the head (h) of the scaphoid bone rotates ventrally so that the ridges (r) on the dorsal aspects of the scaphoid bone and distal radius assume a close-packed position. Note the saddle-shaped facet (s) on the trapezium bone which articulates with the base of the pollical metacarpal bone. Also note the robust tubercle of the scaphoid bone (t).
- b. Medial aspect of same wrist. Note powerful development of the pisohamate ligament (l) which attaches proximally to the elongated pisiform bone (p) and distally to the hamulus of the hamate bone. Direction of dorsiflexion is indicated by arrow. (U) indicates ulna.

propulsive effort of the forelimb during knuckle-walking. Thus the wrist flexors probably act as stabilizing 'adjustable ligaments', to take the tensile components of forces on the carpus, and to prevent excursions of the joints to the limits of their close-packed positions whereby damage might accrue in the articular tissues.

Similarly, the well developed flexor digitorum superficialis and flexor

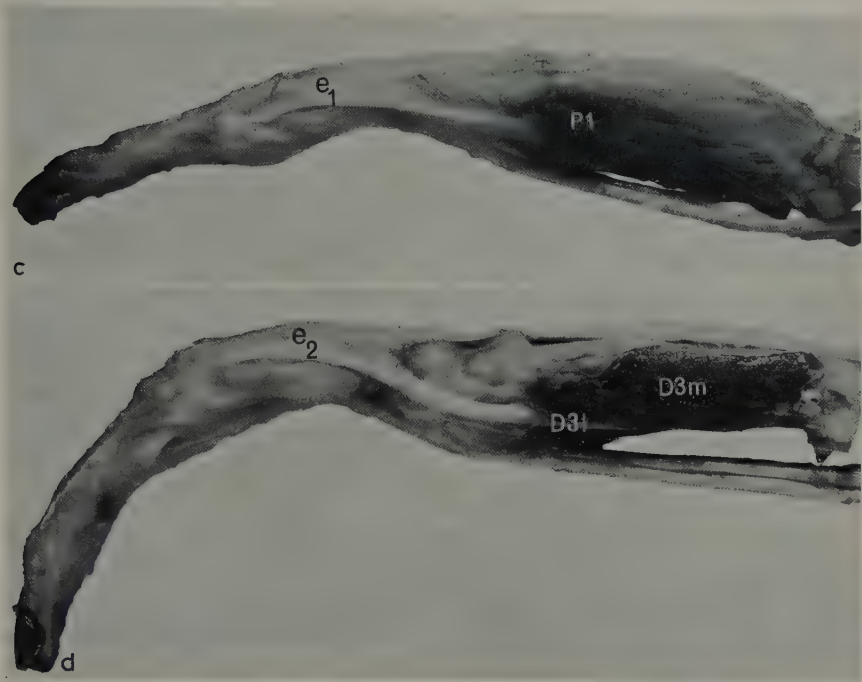


Fig. 8. Medial aspect (bottom row) and distal end (upper row) of left metacarpal III in *Pan troglodytes* (C), *Pan gorilla* (G), and *Pongo pygmaeus* (O). Note the well-developed ridge on the dorsodistal end of this metacarpal in the chimpanzee and gorilla. In *Pongo* the dorsodistal ridging is discontinuous and the articular surface of the metacarpal head does not extend as far dorsally as in *Pan* (photograph by L. SIEMENS, Univ. of Chicago).



Fig. 9. Development of extensor expansions ( $e_1$  and  $e_2$ ) and attachments of the interosseous and lumbrical muscles in manual digits II (a and b) and III (c and d) of *Pan troglodytes*.

- a. On the radial aspect of the index finger, the first lumbrical (L1) is normally the only intrinsic muscle that inserts into the extensor expansion ( $e_1$ ). Both the multipennate (D1m) and longitudinally directed fibers of the first dorsal interosseous muscle attach to the base of the proximal phalanx and capsule of the second metacarpophalangeal joint.
- b. On the radial aspect of the middle finger, the second lumbrical (L2) and the longitudinally directed fibers of the second dorsal interosseous muscle (D2l) insert into the extensor expansion ( $e_2$ ). The bulk of the multipennate component of the second dorsal interosseous muscle (D2m) attaches into the base of the proximal phalanx and capsule of the third metacarpophalangeal joint.



- c. On the ulnar aspect of the index finger, the bulk of the first palmar interosseous muscle (P1) inserts into the extensor expansion ( $e_1$ ).
- d. On the ulnar aspect of the middle finger, the longitudinally directed fibers of the third dorsal interosseous muscle (D3l) insert into the extensor expansion ( $e_2$ ) while the multipennate component (D3m) of the same muscle inserts into the base of the proximal phalanx and the capsule of the third metacarpophalangeal joint.

digitorum profundus muscles may act to maintain the integrity of the carpus during vigorous knuckle-walking. Electromyographic studies of human forearm flexors indicate that the flexor digitorum superficialis muscle is an important stabilizer of the carpus during wrist flexion [BÄCKDAHL and CARSSÖÖ, 1961]. The tendons of the digital flexor muscles are shortened in chimpanzees so that the fingers cannot be extended fully when the wrist is held in passive dorsiflexion. Thus with the digits apposed to the substratum and the metacarpophalangeal joints hyperextended, the digital flexor muscles also may act as 'adjustable ligaments' across the carpus.

The integrity of the hyperextended metacarpophalangeal joints of digits II–V is maintained by intrinsic and extrinsic structures. As in the wrist, features associated with the absorption of compressive stresses are located



on the dorsal aspect of the joints and those that basically take up tensile components are situated on the palmar aspect of the joints.

For instance, the dorsodistal aspects of the second to fifth metacarpal bones frequently possess well developed transverse ridges in adult chimpanzees (fig. 8). The prominent dorsal extension of the articular surface of the metacarpal heads permits the proximal phalanges to be hyperextended to a marked extent. Thus the dorsodistal metacarpal ridges may constitute important articular components in close-packed positions of the metacarpophalangeal joints during static knuckle-walking.

The palmar plates and collateral ligaments are probably not adequate to prevent collapse of the hyperextended metacarpophalangeal joints in close-packed hyperextended positions especially during active knuckle-walking. The shortened tendons of the powerfully developed long digital flexor muscles therefore may be important in maintaining the integrity of these articulations during static and active knuckle-walking.

In active knuckle-walking and landing quadrupedally after a jump, the metacarpophalangeal joints are stressed markedly. During these activities the long digital flexor muscles and the well developed interossei and lumbrical muscles may be called into action to prevent excursions to the limits of the close-packed hyperextended positions of the metacarpophalangeal joints.

Further the action of these extrinsic and intrinsic digital flexor muscles may provide supplementary propulsive forces at the distal extremity of the forelimb during knuckle-walking progression. The long digital flexor muscles are probably in a state of passive stretch toward the end of the forelimb stride due to the permanent shortening of their tendons and their positions ventral to the hyperextended joints.

Similarly, the lumbrical, palmar interosseous and longitudinally directed fibers of the dorsal interosseous muscles, that generally attach to the extensor aponeuroses at a point over the second and third fourths of the proximal phalanges (fig. 9), may be in a state of passive stretch prior to lifting the hand at the end of the forelimb stride. The bulky pennate components of the dorsal interosseous muscles, that attach directly to the bases of the proximal phalanges, are probably important also in executing propulsive forces on the digits during rapid knuckle-walking.

The arrangement of the lateral bands of the extensor aponeuroses is such that the lumbrical and interosseous muscles might be important not only as flexors of the metacarpophalangeal joints but also as extensors of the interphalangeal joints. At the end of the stance phase in forelimb strides extension of the middle phalanges in the knuckle-walking hand would augment the

propulsive effort of the distal extremity. Extension of the middle phalanges may serve thus to coordinate the forelimb stride in the chimpanzee somewhat like flexion of the toes 'smooths out' the lower limb stride in man.

To summarize, the integrity of the wrist joint is probably maintained during static knuckle-walking primarily by intrinsic bone-ligament relationships in special close-packed positions of its component articulations. Extrinsic structures, viz. the antebrachial flexor muscles, are prominent in sustaining carpal integrity in vigorous knuckle-walking activities. The second to fifth metacarpophalangeal joints are supported by intrinsic and extrinsic factors in close-packed hyperextended positions during static knuckle-walking posturing. Again muscle contraction across the ventral aspect of the joints is probably predominant in maintaining the integrity of the articulations in dynamic activities.

### *B. The Hand as a Suspensory Organ*

Several authors have emphasized the adaptations to 'brachiation' in the chimpanzee hand and some have considered it to be fundamentally an 'anatomical hook' for arboreal locomotion [STRAUS, 1940; JOUFFROY and LESSERTISSEUR, 1960; ERIKSON, 1963]. Chimpanzee hands are long in absolute terms and by comparison with trunk height [SCHULTZ, 1956; ERIKSON, 1963]. SCHULTZ [1956, p. 909] found that the average length of the hand in 30 adult specimens of *Pan troglodytes* was 49% of trunk height. Further, the hands of *Pan troglodytes* are slender, hand breadth averaging only 34% of hand length [SCHULTZ, 1956, p. 909].

The long slender configuration of the chimpanzee hand is mainly due to the remarkable length of the second to fifth digital rays. MIDLO [1934, p. 346] found that the average free length of digit III was 86% of palm length in four embalmed specimens. NAPIER and DAVIS [1959, p. 41] determined that the mean lengths of the phalanges of digit III, metacarpal III, and the carpus was 50%, 36%, and 14% of total hand length respectively, in five *Pan troglodytes*. These figures emphasize the considerable length of the non-pollical rays, particularly the phalangeal component.

The proportions of the phalanges in the chimpanzee hand permit digits II-V to be 'double-locked' around slender objects. NAPIER [1960, p. 652] described the anatomical base for this digital postures as follows: 'In chimpanzees the proximal phalanx is of equal or greater length than the combined lengths of the middle and distal phalanges. This permits the finger flexed at

the proximal interphalangeal joint to tuck into the metacarpophalangeal skin-joint at its base thus completely enclosing any slender object so gripped.'

The well developed long digital flexor muscles enable chimpanzees to grip strongly slender twigs and vines as well as larger branches. These muscles insert almost exclusively on the phalanges of digits II-V and the force of their contraction is concentrated on these fingers during suspensory posturing (fig. 10).



*Fig. 10.* Fresh preparation of the right forearm and hand of an adult male *Pan troglodytes*. The flexor carpi radialis, flexor carpi ulnaris, palmaris longus, and pronator teres muscles have been removed to expose the radial head of the flexor digitorum profundus muscle (fpr) and the flexor digitorum superficialis muscle (fds). Note the extensive fasciculation of the long digital flexor muscles. In the hand, the flexor retinaculum, short flexors of digit V, and thenar muscles, have been removed to expose the vestigial pollical flexor tendon (t) and the proximal extent of the lumbical muscles (l). Note the small fleshy attachment of the pollical flexor tendon on the radial tendon of the flexor digitorum profundus muscle (this condition is uncommon in the chimpanzee). (ap) indicates the adductor pollicis muscle.

Permanent shortening of the long digital flexor tendons, which is of advantage to chimpanzees in knuckle-walking, may impair their ability to release branches, particularly at the end of a forward swing. Ricochet arm-swinging, a pattern of arboreal locomotion characteristic of the Hylobatidae, seems to be impossible in *Pan* on anatomical grounds. In ricochet arm-swinging the animal projects itself *upwards* and outwards from beneath a branch by simultaneous retraction of the shoulder and flexion of the elbow joints [TUTTLE, 1969]. The wrist joint must be dorsiflexed during this action in order that the forearm may act effectively as an intercalated segment in the biarticular system. If the long digital flexor tendons are markedly shortened, dorsiflexion of the wrist would further flex the fingers around the base branch and release would be retarded or prohibited. Studies on passive chimpanzees indicate that flexion of the elbow joint is not sufficient to permit extension of the flexed fingers if the wrist is simultaneously dorsiflexed.

Thus, chimpanzees only have the anatomical potential to swing pendulum fashion beneath a branch with shoulder, elbow, and wrist joints aligned (fig. 11). By releasing their grip during the upward segment of an arc of motion, chimpanzees may propel themselves outward and downward. However, this is not an effective mechanism for propelling them along an upward trajectory in the manner of ricochet arm-swinging apes.

The lumbrical and interosseous muscles via their attachments to the lateral bands of the extensor aponeuroses may be important in releasing the flexed digits from suspensory supports, particularly on occasions when the interphalangeal joints are extended while the metacarpophalangeal joints are maintained in partially flexed positions. The distal and middle phalangeal segments of the digital rays are mainly responsible for 'hook-like' grips. Thus by extending the interphalangeal joints independently, the digits need not be extended fully at the metacarpophalangeal joints in order to release a branch. Finally, the extensor digitorum muscle may be important in extending the proximal phalanges and thus assist the digits to clear a base branch.

Chimpanzees possess advanced capabilities to flex and extend independently the manual digits, especially the index finger. This capacity reflects not only refined neurological control of the digits but also the morphological independence of fasciculi in the flexor digitorum superficialis, flexor digitorum profundus, and extensor digitorum muscles [TUTTLE, 1969]. Independent control of the fingers may be of particular value to chimpanzees climbing in small branch regions of trees. Should a few supporting





Fig. 11. Suspensory and prehensile postures in the cheiridia of *Pan troglodytes* and *Pan gorilla*.

- a. Juvenile male chimpanzee hanging from wire of cage roof. Note full extension of wrist, elbow, and shoulder joints and flexion of hip and knee joints.
- b. Juvenile male chimpanzee arm-swinging across the roof of wire cage. Note full extension of right forelimb joints and rotation of right shoulder joint.
- c. Palmar aspect of chimpanzee hand leisurely gripping the wire of a cage side.
- d. Right foot of a juvenile gorilla gripping a bar in cage roof. Compare with orangutan in fig. 4.g (a and b by L. SIEMENS, Univ. of Chicago; c and d by I. BERNSTEIN and F. KIERNAN, Yerkes Regional Primate Research Center).

twigs break or slip out of the flexed fingers, the hanging animal can grasp new branches without necessarily opening the whole hand.

In summary, although the chimpanzee hand is specialized for knuckle-walking, it retains some features of a suspensory organ. The morphological limitations of wrist mobility and permanent shortening of the long digital flexor tendons restrict somewhat the range of arboreal acrobatic activities in chimpanzees, particularly by comparison with gibbons. But the morpho-

logical compromises in the hand between terrestrial and arboreal functions do not limit markedly the arboreal foraging and feeding capabilities of *Pan troglodytes*.

### *C. Locomotion-Manipulation Compromises*

The pollex of *Pan troglodytes* often has been described as 'reduced' and the shortening of this digit has been associated generally with the 'habit of brachiation' [ERIKSON, 1963]. SCHULTZ [1956, p. 909] found that the length of the adducted thumb, as measured from the most distal point on the styloid process of the radius to the most distal point on the pulp of the thumb, is 47% of greatest hand length. MIDLO [1934, p. 346] described the free length of digit I as 44 percent of palm length. ASHLEY-MONTAGU [1931, p. 303] noted that the average pollical index (i.e. length of pollical phalanges  $\times 100$ /length of phalanges of digit III) was 35.4 in a sample of 16 *Pan troglodytes*. NAPIER and NAPIER [1967, p. 401], studied skeletal materials and described the pollical ray as 33% of the greatest length of the hand.

'Reduction' of thenar structures is most notable in the development of the long flexor tendon. In a survey of literature supplemented by original dissections, STRAUS [1942] noted that the long flexor tendon was absent completely in 30%, 'a functionless rudiment' in 22%, and 'entirely developed in direct functional continuity with the radial muscle belly of the flexor digitorum profundus in 48%' of 47 chimpanzee forelimbs. In the 17 chimpanzees that I have dissected, a fine tendon was observed extending from the fascia that surrounds the long digital flexor tendons in the carpal tunnel to the terminal phalanx of the pollex. But these tendons were not attached firmly to the radial tendon of the flexor digitorum profundus muscle and thus appear to have been ineffective as flexors of the thumb (fig. 12). The pollical tendon frequently may be found attached to the fascia on the long flexor tendons more firmly in preserved than in fresh specimens. This may explain, to a great extent, the high incidence of specimens to which were attributed a 'functional' pollical tendon in the data summarized by STRAUS.

Although the chimpanzee thumb generally lacks an extrinsic flexor mechanism, the intrinsic pollical muscles are well developed and are attached such that the pollex may act as a proficient manipulatory organ. The total mass of intrinsic thumb muscles is approximately 24% of total intrinsic hand muscles (table II). The adductor pollicis muscles constitutes somewhat less than one-half of total intrinsic thumb muscles, a proportion similar to that in the human hand (table II, and TUTTLE, 1969).

In *Pan troglodytes*, the adductor pollicis muscles possess tendinous attachments to the ventral aspect of the terminal phalanx. Both the oblique and transverse heads, which are generally clearly discernible in the adductor pollicis muscle, insert, in part, via these tendons (fig. 12). Further, the 'primary volar interosseous muscle of Henle', which is present as an entity in approximately one-fourth of chimpanzee hands, also possesses a tendinous insertion to the pollical terminal phalanx (fig. 12).

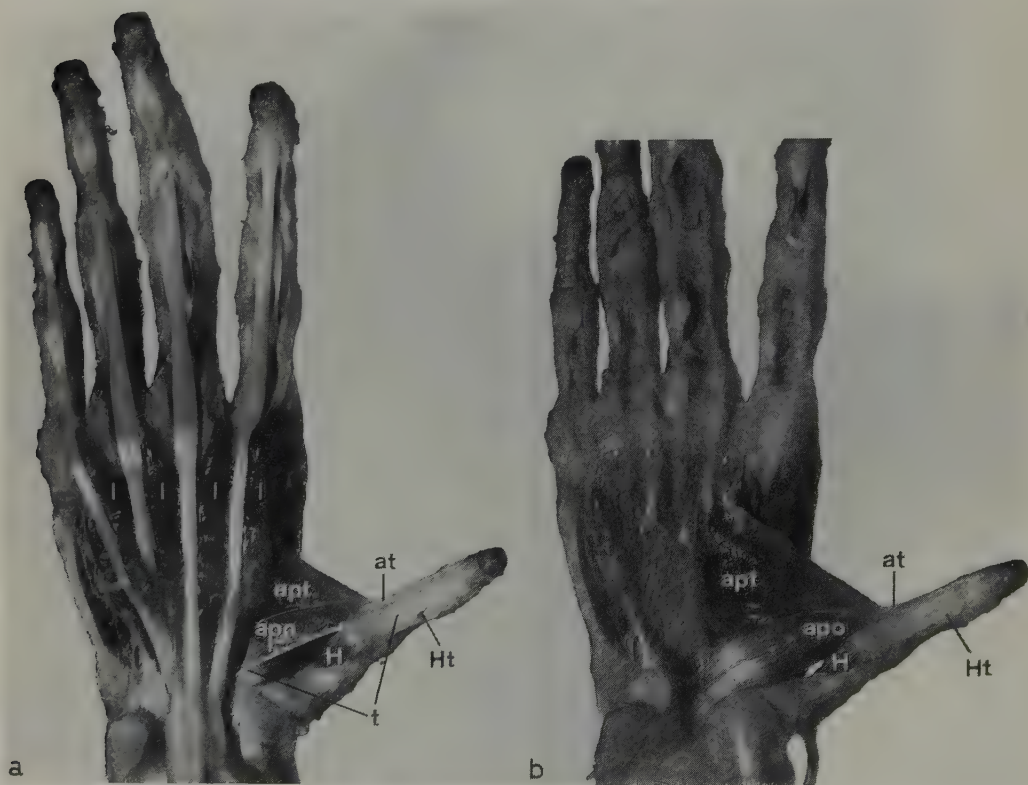


Fig. 12. Fresh preparations of palmar aspect of right hand in an adult male *Pan troglodytes*.

- a. Flexor retinaculum, short flexor muscles of digit V and thenar eminence muscles have been removed to expose the lumbrical muscles (l), vestigial pollical tendon (t) of the flexor digitorum profundus muscle, and muscles of the adductor pollicis complex. Note that the transverse (apt) and oblique (apo) heads of the adductor pollicis muscle and the 'primary volar interosseous muscle of Henle' (H) send tendinous extensions (at and Ht, respectively) to the distal phalanx of the pollex.
- b. Same hand with lumbrical muscles and long digital flexor tendons removed.



The configuration of joints in the chimpanzee pollex constitute the morphological bases for the fact that the organ generally acts as a unit with the primary potential for movement located in the carpometacarpal articulation. The first carpometacarpal joint is a relatively shallow saddle articulation surrounded by a thin loose capsule. Movement is permissive in most directions. Excursions at the carpometacarpal joint appear to be limited basically by the heavy cuff of thenar muscles in which it is deeply buried. Moreover, the first metacarpal bone is rather closely webbed to the palm by soft tissues.

Concordant with the considerable depth of the carpal tunnel in *Pan*, the trapezium is set at an angle of 90° or more to the plane of the posterior margin of the capitate bone [NAPIER and DAVIS, 1959, p. 43–44]. Thus the thumb is permanently in a posture from which to oppose effectively the index and other fingers (fig. 13).

The first metacarpophalangeal joint in *Pan troglodytes* is basically an ellipsoid articulation, but in some individuals it approaches a planar configuration [TUTTLE, 1969]. Rounding is commonly present on the distal extremity and ventral aspect of the metacarpal head, but it seldom extends onto the dorsodistal aspect of the bone. Thus, in contrast with the second to fifth metacarpophalangeal joints, hyperextension is restricted greatly at the first metacarpophalangeal articulation. Side-to-side deviations also are differentially limited (range = 0–40°) concordant with the amount of flatness of the first metacarpal head.

Rotatory movements at the pollical metacarpophalangeal joint are facilitated by the single shallow configuration of the base of the proximal phalanx and by the absence of marked irregularities on the head of the metacarpal bone, particularly in those specimens with rounded metacarpal heads (fig. 14). A small amount of medial rotation at the metacarpophalangeal articulation may be of advantage in manipulating small food objects and grooming.

The pollical interphalangeal joint has a condylar configuration and movements are confined mainly to a flexion-extension axis (fig. 14). Further, the distal articular surface of the proximal phalanx slopes anteriorly, often at an acute angle to the posterior aspect of the shaft of the bone. This not only results in the appearance of a permanently flexed terminal phalanx but also serves as an effective brake to full extension and hyperextension of the interphalangeal joint [TUTTLE, 1969]. The intrinsic flexor muscles of the terminal phalanx probably also assist to retain the 'flexion set' of the interphalangeal joint when the thumb is used for powerful prehension.



Whereas flexion of the chimpanzee thumb is effected by intrinsic muscles, extension is produced by extrinsic muscles [TUTTLE, 1969]. The distal attachment of the pollical extensor muscles, particularly the abductor pollicis longus, is concordant with the carpometacarpal joint serving as the primary location of thumb motion. In individual chimpanzees the abductor pollicis longus muscle inserts into the radial base of the first metacarpal bone, the trapezium bone, or both [STRAUS, 1941, p. 206]. Chimpanzees lack a tendi-

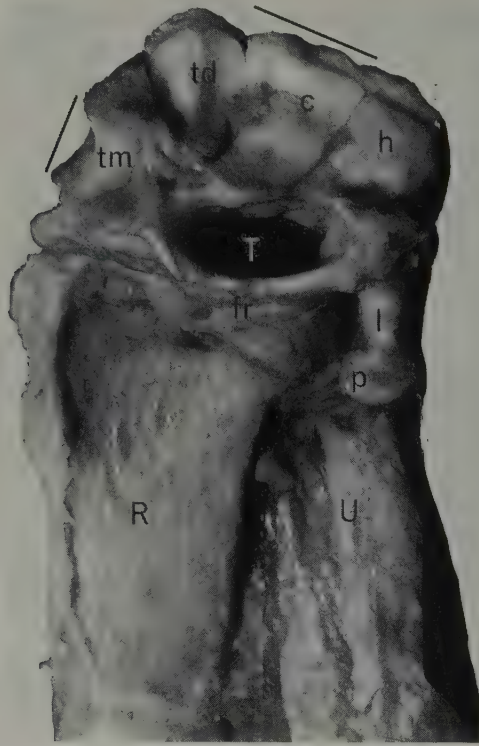


Fig. 13. Fresh preparation of carpal tunnel (T) and distal row of carpal bones in the volarflexed left wrist of an adult male *Pan troglodytes*. The digital rays have been removed to expose the distal articular surfaces of the trapezium (tm), trapezoid (td), capitate (c), and hamate (h) bones. Note that the dorsal aspect of the trapezium bone (tm) is set at approximately right angles to the dorsal aspect of the capitate bone (c). The powerfully developed flexor retinaculum (fr) attaches to the trapezium and scaphoid bones laterally and the pisiform and hamate bones medially. Note the well-developed pisohamate ligament (l) that is attached proximally to the pisiform bone (p) and compare with fig. 7b. R and U indicate radius and ulna, respectively.

*Fig. 14.* Bones comprising the left first manual rays of two adult female *Pan troglodytes*: a and b, lateral aspect of metacarpal I; c and d, distal articular surface of first metacarpal; e and f, proximal articular surface of proximal phalanx; g and h, lateral aspect of proximal phalanx; i and j, distal articular surface of proximal phalanx; k and l, articular surface of distal phalanx; m and n, ventral aspect of distal phalanx. Compare the rounded (a) versus flattened (b) configurations of the two metacarpal heads and note the acute slope of the distal articular surface of the proximal phalanx (g and h) which contributes to the permanent 'flexion set' of the distal phalanx in chimpanzee thumbs (photograph by L. SIEMENS, Univ. of Chicago).



nous insertion comparable to that of the extensor pollicis brevis muscle in man.

In summary, although the thumbs of chimpanzees are relatively short compared with the length of the other manual digits, they have been retained as efficient manipulatory organs and play a prominent role in the selective feeding and grooming patterns of the animals. The precision with which chimpanzees utilize their thumbs suggests that selective biases for proficient manipulation have continued to advance their pollices despite the shift of extrinsic muscles from manipulative to special locomotive functions.

During manipulative activities, the bony elements of the pollical ray generally act as a unit, with only minor degrees of flexion and rotation at the metacarpophalangeal and interphalangeal joints. Displacements at these joints are greatly minimized by morphological features. Thus the major point of motion is located at the carpometacarpal joint which is limited in passive movements by the bulky cuff of intrinsic muscles that nearly surrounds the loose articular capsule. These intrinsic pollical muscles are specially adapted to ensure the coordinated action of the distal and proximal phalanges by tendinous extensions to the former bone.

#### V. MORPHOLOGICAL AND FUNCTIONAL ASPECTS OF CHIMPANZEE FEET

The feet of *Pan troglodytes*, like their hands, consist of morphological compromises between terrestrial and arboreal supporting and locomotive functions.

The major dichotomy in pedal functional morphology is concordant firstly with supporting and propulsive actions on broad horizontal substrates and secondly with prehensile actions in climbing tree trunks and securing positions atop flexible branches.

But whether in trees or on the ground, chimpanzee feet are subjected predominantly to compressive stresses. By contrast with the hands, the feet in chimpanzees are rarely subjected to extreme tensile stresses in suspensory posturing and locomotion and they are not utilized extensively for refined manipulation of foods and other small objects.

##### *A. Morphological Bases of Plantigrade Habitus*

The feet of chimpanzees are relatively long, being 50% of trunk height in embalmed adult specimens and 47% of trunk height in macerated adult

specimens [SCHULTZ, 1956, p. 909 and 1963, p. 155]. The phalanges (36%) and the metatarsus (30%) together constitute the greater portion of foot length in *Pan troglodytes* [SCHULTZ, 1963, p. 165].

SCHULTZ [1963] demonstrated that in the chimpanzee foot, the 'power arm', as measured from the most proximal point on the tuber calcanei to the center of the trochlea tali, is approximately 28% of the 'load arm', as measured from the center of the trochlea tali to the distal extremity of metatarsal III. The relative length of the 'power arm' thus determined in the chimpanzee foot is surpassed only by those of gorillas ( $\bar{x}$  = 46%) and man ( $\bar{x}$  = 39%) among primates [SCHULTZ, pp. 156-157].

Associated with the relatively well developed 'power arm' in the foot skeleton, the plantar flexor muscles, viz. gastrocnemius, soleus and plantaris, are the major potential functional unit in the chimpanzee leg. The plantar flexors constitute approximately 44% of total leg muscles in *Pan troglodytes* (table IV).

The tendons of the tibialis anterior, tibialis posterior, peroneus longus, and flexor digitorum tibialis and fibularis muscles pass very close to the axis of the ankle joint and thereby probably subserve stabilizing functions during the hindlimb stride.

Chimpanzees lack any semblance of the longitudinal arch of the human foot and thus appear to be 'flat-footed' [MORTON, 1924; ELFTMAN and MANTER, 1935]. The sustentaculum tali slopes ventromedially at an acute angle. The calcaneocuboid and the calcaneonavicular articulations, which together constitute the transverse tarsal joint, are permissive of notable amounts of flexion, extension, and rotation.

During the initial phase of heel-raising, the weight of the animal passes onto the medial aspect of the foot while a considerable portion of the sole is still in contact with the ground. The navicular and medial cuneiform bones are the major tarsal elements that bear the compressive forces incurred by the foot during this semi-plantigrade stance of the hindlimb stride [MORTON, 1924; ELFTMAN and MANTER, 1935]. The line of leverage falls between the adducted hallux and the remaining digits [MORTON, 1924].

As the weight of the animal passes over the foot, the widely abducted hallux often flexes and serves as a strut to transfer some of the load onto the lateral aspect of the sole. Sometimes, prior to the swing phase of the stride, the hallux is flexed so strongly that an arch is formed and the distomedial aspect of the sole loses contact with the substratum.

Chimpanzees lack a 'ball of the foot' [ELFTMAN and MANTER, 1935]. The middle and distal phalanges of digits II-V frequently are flexed throughout



the stance phase of the hindlimb stride, giving the impression of a 'ball'. The proximal phalanges are extended or hyperextended. Thus, the 'ball' lies distal to the metatarsal heads and generally does not bear a great amount of weight. The foot usually is elevated before the load can pass on to the lateral four toes. In some animals the dorsum of the flexed toes may brush against the ground, but again these contacts are brief and do not appear to contribute much support in the stance phase of the stride. Further, the digits do not provide an effective 'toe snap' of the sort that is significant in 'smoothing' the human stride at the end of the stance phase.

The metatarsophalangeal joints of digits II-V permit a considerable amount of hyperextension ( $\bar{x} = 53^\circ$ ). This flexibility in the distal extremity of the foot allows some weight to fall on the metatarsal heads instead of the dorsum or ends of the curled toes. The toes may be extended widely in passive animals, even when the metatarsophalangeal joints are held in hyperextension. This indicates that the tendons of the flexor digitorum muscles are not shortened markedly and that the potential for extension of the digits probably exists in active chimpanzees. Thus, in many chimpanzees, flexion of the second to fifth toes during plantigrade locomotion is probably associated with the fact that the phalanges are too long to serve consistently as efficient supporting or propulsive levers in fully extended postures. SCHULTZ [1963, pp. 162-163] provides evidence that among Old World monkeys, '*Papio*, *Theropithecus* and *Erythrocebus* have comparatively shorter phalanges than any of the arboreal forms.' In man, whose phalanges also contribute significantly to propulsion, the phalanges of digit III constitute only 19 percent of total length of the foot skeleton [SCHULTZ, p. 163].

### *B. The Foot as a Prehensile Organ*

Although chimpanzee feet function effectively as plantigrade supporting and locomotor organs and although comparative studies reveal trends toward increased development of the 'power arm' and plantar flexor muscles, the pedal cheiridia appear to be adapted primarily for powerful arboreal prehensile functions.

The opposable hallux is long and robust in absolute and relative terms. SCHULTZ [1963, p. 165] found that the length of ray I is 70% of the length of ray III in *Pan troglodytes*. SCHULTZ further demonstrated that metatarsal I is 81.5% of the length of metatarsal III and that the hallucal phalanges are 60.5% of the length of the phalanges in digit III. In a more limited sample

of chimpanzees, MIDLO [1934, p. 34] noted that the 'free length of digit I' was 44 percent of sole length. This mean value was highest in *Pan* among the small available samples of the Pongidae.

The distal ends of the metatarsal bones exhibit notable torsion toward the line of leverage. Torsion is greatest in the second metatarsal and decreases preaxially and postaxially in the remaining metatarsus. For instance, MORTON [1922, p. 312] found that the second, third, and fourth metatarsal bones evinced 35, 20 and 10 degrees of medial torsion, respectively. The first and fifth metatarsal bones were essentially free of torsion. However, MORTON [1922, p. 312] described the hallucal metatarsal as follows: '... instead of torsion, the entire bone seems to be remodelled so that even the dorso-plantar axis of its base lies practically in the same plane as the flexor-extensor axis of the head.'

The shafts of the metatarsal bones and the proximal and middle phalanges exhibit plantar curvature, especially in digits II-V. The ellipsoid articular surface of the metatarsophalangeal joints are permissive of flexion-extension and rotatory movements. The interphalangeal joints, by contrast, are condyloid articulations which prohibit rotation, side-to-side deviations, and hyperextension. The tarsometatarsal and intermetatarsal joints of digits II-V are basically planar and are limited to small amounts of gliding.

Because of its essentially cylindrical configuration, the first tarsometatarsal joint differs markedly from the planar hallucal joint in man and from the other tarsometatarsal joints in the chimpanzee foot. The hallucal tarsometatarsal joint of *Pan troglodytes* is especially suited to extensive movements along an axis of flexion-extension. However, due to conjunct rotation in the joint, as the hallux approaches the close-packed extended position it is widely abducted in relation to the remaining digits. Although the interval between the first and second metatarsal bones is filled with soft tissues, the hallux may be 'abducted' to the extent that an angle of 135° exists between the free portions of digits I and II (table I).

In *Pan troglodytes*, the hallux is provided with extremely well developed extrinsic and intrinsic muscles that facilitate powerful prehensile actions. For example, a large tendon of the flexor digitorum fibularis muscle, which constitutes approximately 11.1 % of total leg muscles, inserts into a deep excavation on the broad plantar base of the hallucal distal phalanx.

Similarly, the peroneus longus muscle, which constitutes approximately 7.7% of total leg muscles, attaches via a stout tendon to the ventrolateral

aspect of the prominent tuberosity on the base of the first metatarsal bone. The tendon of the peroneus longus muscle occupies an osseofibrous tunnel which is comprised in part of deep grooves on the plantar aspects of the cuboid and lateral cuneiform bones. As the peroneus tendon enters the plantar tunnel on the lateral aspect of the sole, it turns sharply medially. This pulley-like arrangement of the peroneus tendon is admirably situated such that the muscle acts as a powerful flexor of the hallux.

The intrinsic muscles of the chimpanzee foot also are developed with an emphasis on capacities for hallucal prehensility. The intrinsic pedal muscles preaxial to digit III are 2.8 times the relative mass of those postaxial to digit III in *Pan troglodytes* (table V). This is mainly due to the development of the intrinsic hallucal muscles which constitute approximately 48% of total intrinsic foot muscles (table IV).

The 'short hallucal flexors', which constitute more than one-fourth of the total intrinsic foot muscle mass (table IV) are mainly two-joint muscles that act to stabilize and direct movements at the tarsometatarsal joint. In addition, the abductor and flexor hallucis brevis muscles are probably important rotators and accessory flexors of the metatarsophalangeal joint.

The adductor hallucis muscle is large in *Pan troglodytes*, constituting approximately one-fifth of total intrinsic foot muscles (table IV). It has an extensive insertion to the ventrolateral base of the proximal phalanx, lateral sesamoid bone, and capsule of the metatarsophalangeal joint. In some animals it may insert also to the distal shaft of the first metatarsal bone or to the proximal shaft of the proximal phalanx, send a tendinous extension to the ventrolateral base of the distal phalanx, or possess any combination of these attachments. Thus it is a powerful muscle for flexing the proximal phalanx and sometimes also the distal phalanx, as well as 'adducting' the hallux as a unit during vigorous prehensile activities. Further, it is probably an important stabilizer of the first tarsometatarsal joint when the hallux is utilized for powerful grasping functions.

Although the large opposable hallux is the strongest single component in the pedal prehensile pattern of *Pan troglodytes*, the lateral toes also demonstrate features that may be correlated with arboreal prehensile capabilities of the foot.

The phalanges of digits II-V exhibit proportions that would permit a 'double-locking' mechanism in the foot similar to that which NAPIER [1960] described for the hand. The proximal, middle, and distal phalanges constitute 51%, 31%, and 18%, respectively, of the total length of pedal digit III [SCHULTZ, 1963, p. 165].

The extrinsic digital flexor muscles (flexor digitorum tibialis and fibularis) comprise approximately 9% of total intrinsic foot muscles (table IV). The arrangement of the tendons of these muscles ensures convergence of the digits during opposition. The two principle tendons of the flexor digitorum tibialis muscle insert to the distal phalanges of digits II and V whereas the flexor digitorum fibularis tendons insert principally to the distal phalanges of digits I, III, and IV. Thus the tibialis muscle flexes and converges the second and fifth toes while the fibularis muscle acts to flex and oppose the hallux to the lateral toes.

The flexor digitorum brevis muscle is probably an accessory flexor of the lateral digits. It was inserted to the middle phalanges of digits II, III, and IV in 100% (7/7) and digit V in 28.6% (2/7) of available chimpanzee specimens. The flexor accessorius (quadratus plantae) was vestigial (2) or absent (5) in the 7 specimens.

Finally, several features associated with the plantigrade habitus of chimpanzee feet also may be related, to some extent, with arboreal climbing capabilities. For instance the well developed plantar-flexing leverage mechanism and flexible transverse tarsal joint are probably important to chimpanzees in climbing tree trunks and large vertical or steeply inclined branches. Thus, as the digits grip the substratum, the heel may be raised thereby supplementing the propulsive thrust of the extending hindlimb.

### *C. Summary*

The foot of the chimpanzee exhibits fewer features than the hand that may be attributed unequivocally to selection for terrestrial versus arboreal locomotive proficiency. By comparison with *Homo*, the pedal cheiridia of *Pan troglodytes* are more like 'hands' than 'feet' whereas their manual cheiridia are adapted to subserve special supporting and locomotive functions often identified with the latter.

The massy plantar flexor muscles and relatively long skeletal 'power arm' equip the chimpanzee foot with a propulsive mechanism that may supplement the thrust of the extending hindlimb both in vertical climbing and plantigrade striding.

The long heavily muscled hallux not only provides powerful prehensile capabilities in climbing, but also serves sometimes as a strut in terrestrial locomotion to transfer part of the load onto the lateral aspect of the foot.



The second to fifth toes are basically adapted to arboreal prehensile functions and do not appear to be very effective as supporting and propulsive organs during plantigrade progression.

#### VI. INTERTAXONAL COMPARISONS OF GREAT APE HANDS AND FEET

In many features, the cheiridia of chimpanzees are intermediate between those of gorillas and orangutans though each of the three great apes possesses some features that are uniquely adapted to its respective mode.

##### *A. External Features and Bones*

The hand of the orangutan, like that of the chimpanzee, is long and slender, whereas that of the gorilla is comparatively short and broad [MIDLO, 1934; SCHULTZ, 1956; ERIKSON, 1963]. Interdigital webbing is marked in the hands of gorillas which adds to the fore-shortened appearance of the fingers.

The proportions of the phalanges in the hand of *Pongo* constitute the basis for a 'double-locking' mechanism similar to that in *Pan troglodytes* [NAPIER, 1960].

The pollex is short in *Pongo pygmaeus* and long in *Pan gorilla* when compared with that of *Pan troglodytes* [ASHLEY-MONTAGU, 1931; SCHULTZ, 1956; NAPIER and NAPIER, 1967]. But according to studies by NAPIER and NAPIER [1967, pp. 400-402], the 'opposability index' (thumb length  $\times$  100/index ray length) probably does not separate discretely *Pan troglodytes* ( $\bar{x}$  = 42, range: 38-44) from *Pongo pygmaeus* ( $\bar{x}$  = 39, range: 36-44). *Pan gorilla*, by contrast, appears to be distinct from the other Pongidae in regard to the 'opposability index' ( $\bar{x}$  = 48, range: 43-51).

The hands of the African apes are distinguished from those of orangutans in possessing typical friction skin or 'knuckle pads' on the dorsal surfaces of the middle phalanges [SCHULTZ, 1936; ELLIS and MONTAGNA, 1962; MONTAGNA and YUN, 1963].

The bony features that are associated with knuckle-walking in chimpanzees, such as the dorsodistal ridges on metacarpals II-V (fig. 8), deep excavation of the distal articular surface of the radius, and the prominent scaphoid ridge and tubercle (fig. 15), generally are well-developed also in gorillas [TUTTLE, 1967]. In orangutans, the articular surfaces of the metacarpal



Fig. 15. Distal radii and scaphoid bones of *Pongo pygmaeus* (O), *Pan troglodytes* (C), and *Pan gorilla* (G) and the os centrale (oc) of *Pongo*. Note the prominent ridges (rr) on the dorsodistal border of the radius and the scaphoid bone in *P. troglodytes* and *P. gorilla*. h indicates the head of the scaphoid bone which articulates with the distal radius. The robust scaphoid tubercle t indicates the robust scaphoid tubercle.

heads do not extend notably onto the dorsal aspect of the metacarpus (fig. 8); the distal articular surface of the radius is shallow; and an unfused os centrale is commonly interposed between the scaphoid and distal row of carpal bones (fig. 15).

Fusion of the os centrale generally occurs in late fetal and infantile stages in the African apes but only rarely in middle or old age in orangutans [SCHULTZ, 1936, p. 273 and 1956, p. 948]. Early fusion of the os centrale in the African apes may be related to knuckle-walking posturing of the hand and concordant special distribution of compressive stresses in the carpus. The occasional late fusion of the os centrale in some orangutans may be related to the fact that they 'fist-walk' atop large branches or on cage floors and use their fists to pack down nesting materials.

In many regards, the feet distinguish the three taxa of great apes more clearly than their hands (fig. 16). The feet of chimpanzees and gorillas have wide soles, relatively long and wide heels, and long halluces that attach near the middle of the sole [MIDLO, 1934, p. 379]. By contrast, the feet of orangutans have an elongated hook-like appearance with relatively short, narrow



Fig. 16. Plantar aspect of the left foot in an adult *Pan troglodytes* (a), subadult *Pongo pygmaeus* (b), and juvenile *Pan gorilla* (c). Note the extensive interdigital webbing in the western gorilla and between digits II and III in the chimpanzee. Also note the robustness of the hallux and heel in the African apes (photographs by F. KIERNAN, Yerkes Regional Primate Research Center).

heels, and diminutive halluces that diverge from the sole 'nearer to the heel than in any other genus of the Anthropoidea' [MIDLO, 1934, p. 378].

In comparison with the feet of the African apes, the considerable length of the orangutan foot (viz., 62 % of trunk height) is primarily due to the marked elongation of the phalanges of digits II-V [SCHULTZ, 1956; p. 909 and 1963, p. 154].

The reduction of the hallux in *Pongo pygmaeus* has advanced so far that the nail and distal phalanx are absent in more than 60 percent of specimens and the proximal phalanx is absent occasionally [SCHULTZ, 1936, 1941, and 1968; STRAUS, 1942; TUTTLE and ROGERS, 1966]. Hallucal reduction has implicated not only the phalanges but also the first metatarsal bone [SCHULTZ, 1963].

Data collected by TUTTLE and ROGERS [1966] and SCHULTZ [1968, p. 134] further demonstrate that congenital absence of hallucal phalanges and nails is a sex-influenced trait, being significantly more common in females.

The major features that distinguish the feet of chimpanzees from those of gorillas are the greater development of interdigital webbing, the relatively short second to fifth toes, and the more prominent heel in the latter (fig. 16). According to MIDLO [1934, p. 380]. 'In *Pan* the webs reach usually only halfway along the length of the basal phalanges, whereas in *Gorilla* they extend, as a rule, as far as the articulations between the proximal and middle phalanges, where they form a transverse fold.' These interdigital webs of friction skin and underlying connective tissue serve as a functional extension of the sole distally [SCHULTZ, 1927; MIDLO, 1934].

Gorillas and chimpanzees from different localities exhibit considerable variation in development of pedal interdigital webbing. For instance, SCHULTZ [1968, p. 132] demonstrated that soft tissues unite the hallux with the sole more extensively in eastern than western gorillas. SCHULTZ [1968, p. 132] further noted that 'the grasping ability of the first toe is decidedly more limited (in eastern mountain gorillas) than in typical western gorillas and the other toes appear to be remarkably short and better suited for terrestrial than arboreal life'.

REYNOLDS [1967, p. 61] has described partial webbing between the second and third toes as a 'frequent feature' of *Pan paniscus*. This trait is not restricted to bonobos among the great apes since a similar condition exists in both feet of an adult male common chimpanzee at the Yerkes Regional Primate Research Center (fig. 16).

The second to fifth toes of *Pan gorilla* appear short not only because of interdigital webbing but also because of the relative shortness of the phalan-



ges. SCHULTZ [1963, p. 163] found that in *Pan gorilla* the phalanges of digit III constitute approximately 32 % of total skeletal foot length. This value is considerably lower than values of *Pongo* (43 %) and *Pan troglodytes* (36 %). The apparent shortness of the phalanges of the second to fifth toes in *Pan gorilla* is probably also the result of the increased length of the tarsus. However, the relative length of the toes in gorillas permit them to be applied consistently in extended positions during plantigrade posturing and locomotion.

The massive development of the heel in *Pan gorilla* is correlated not only with the great size and plantigrade habitus of the species but also with the increased development of the tarsus, especially the 'power arm' in the foot skeleton. In *Pan gorilla*, the average ratio of the 'power arm' to 'load arm' is 46.1, a value considerably larger than values of *Pongo pygmaeus* (19.6), *Pan troglodytes*, and *Homo sapiens* [SCHULTZ, 1963, p. 157].

Gorillas and orangutans exhibit less torsion of the distal metatarsal bones than chimpanzees, but for different functional reasons. The feet of gorillas are more advanced for plantigrady than those of chimpanzees whereas in orangutans, the feet are basically four-digit suspensory organs [MORTON, 1922 and 1924].

### B. Joints

The manual joints of *Pan troglodytes* are more similar to those of *Pan gorilla* than *Pongo pygmaeus*. The differences between the African and Asian pongids are related primarily to the knuckle-walking habits of chimpanzees and gorillas and the predilection for suspensory posturing in the orangutan. Thus, in contrast with orangutans, gorillas and chimpanzees exhibit notable restrictions to dorsiflexion (fig. 17) and adduction (fig. 18) in the wrist and permissibility of metacarpophalangeal hyperextension (fig. 19).

Similarly, the second to fifth metatarsophalangeal joints in gorillas, like those of chimpanzees, evidence greater hyperextensibility than those of orangutans (fig. 20 and 21). In *Pongo*, the metatarsal and proximal and middle phalangeal bones of digits II-V possess a marked degree of plantar curvature. Further, the pedal interphalangeal joints, like the metatarsophalangeal, metacarpophalangeal and manual interphalangeal joints, have a permanent flexion set that contribute to the hook-like appearance of the foot. These features of the bones and joints enable the orangutan foot to function as a suspensory supporting organ in a manner very different from the plantigrade feet of chimpanzees and gorillas.

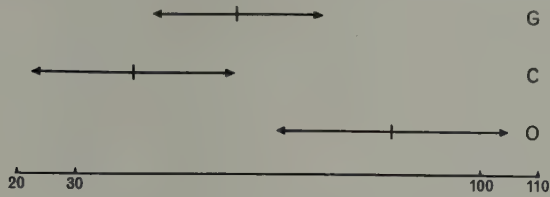


Fig. 17. Mean (vertical bar) and 90% limits (double-tipped arrow) for the degree of dorsiflexion in the wrist of *Pan gorilla* (G), *Pan troglodytes* (C), and *Pongo pygmaeus* (O).

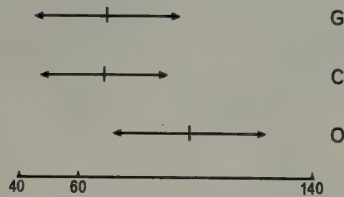


Fig. 18. Mean (vertical bar) and 90% limits (double-tipped arrow) for the degree of aduction in the wrists of *Pan gorilla* (G), *Pan troglodytes* (C), and *Pongo pygmaeus* (O).

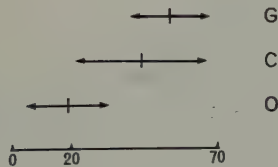


Fig. 19. Mean (vertical bar) and 90% limits (double-tipped arrow) for the degree of hyperextension in metacarpophalangeal joints II-V of *Pan gorilla* (G), *Pan troglodytes* (C), and *Pongo pygmaeus* (O).

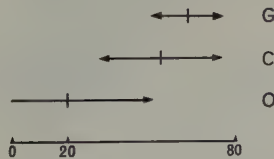


Fig. 20. Mean (vertical bar) and 90% limits (double-tipped arrow) for the degree of hyperextension in metatarsophalangeal joints II-V of *Pan gorilla* (G), *Pan troglodytes* (C), and *Pongo pygmaeus* (O).



Fig. 21. Maximum extent of passive hyperextension of metatarsophalangeal joints II-V in the left foot of an adult *Pan troglodytes* (a), subadult *Pongo pygmaeus* (b), and juvenile *Pan gorilla* (c) (photograph by F. KIERNAN, Yerkes Regional Primate Research Center).



Fig. 22. Left foot of an adult male *Pan troglodytes* in maximum passive eversion (a), at rest (b), and in maximum passive inversion (c) (photographs by F. KIERNAN, Yerkes Regional Primate Research Center).

### C. Muscles

The total relative mass of the leg and foot muscles is larger than the total mass of the extrinsic and intrinsic hand muscles in *Pan troglodytes*. By contrast, in *Pongo pygmaeus* the total mass of the extrinsic and intrinsic muscles of the hand are larger than the total mass of the extrinsic and intrinsic pedal muscles. *Pan gorilla* appear to have nearly equal development of total hand and total foot musculature. Thus, *Pan gorilla* is intermediate between *Pan troglodytes* and *Pongo* in the relative development of total foot and hand muscles but they are somewhat closer to the former taxon (fig. 23).

The major difference between *Pan troglodytes* and *Pongo* in relative development of total hand and total foot muscles is due to the relatively

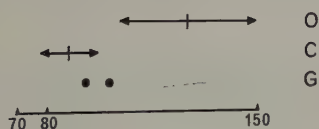


Fig. 23. Ratio expressing the relative weight of total forearm and hand muscles as a percentage of total leg and foot musculature in the Pongidae. (O, *Pongo pygmaeus*; C, *Pan troglodytes*; G, *Pan gorilla*; vertical bars, mean values; double-tipped arrows, 90% limits; dots, individual specimens.)



great difference in the development of the leg muscles, antebrachial muscles, or both. Whereas orangutans exhibit a statistically highly significant difference from chimpanzees in the relative development of extrinsic hand and foot muscles, they are not significantly different from one another in the relative development of total intrinsic manual and pedal muscles (fig. 24 and 25).

The leg and antebrachial muscles are nearly equally developed in gorillas. Thus, gorillas are intermediate between orangutans and chimpanzees, but closer to the latter, in the development of leg muscles by comparison with development of antebrachial muscles (fig. 24). Gorillas are, however, distinct from and not intermediate between chimpanzees and orangutans in the relative development of total intrinsic hand and foot muscles (fig. 25). Gorillas have considerably less preponderance of intrinsic foot muscles than either chimpanzees or orangutans [TUTTLE, in press b].

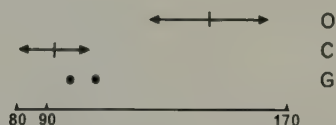


Fig. 24. Ratio expressing the relative weight of total forearm muscles as a percentage of total leg musculature in the Pongidae (symbols as in fig. 23).

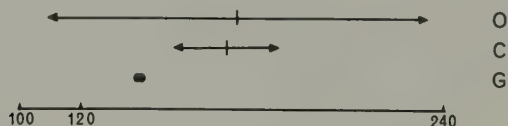


Fig. 25. Ratio expressing the relative weight of total intrinsic foot muscles as a percentage of total intrinsic hand muscles in the Pongidae (symbols as in fig. 23).

The African apes generally differ from orangutans in the relative development of the hindlimb muscles more than forelimb muscles. Chimpanzees are highly significantly different from orangutans in relative mass of the plantar flexors, digital flexors, dorsiflexors, and digital extensors, when these muscle groups are expressed as a percentage of total leg musculature [TUTTLE, in press b].

The plantar flexors (fig. 26) are the predominant group of muscles in the legs of all great apes, but in orangutans the extrinsic digital flexors (fig. 27) are nearly as large as the plantar flexors. In chimpanzees and gorillas the digital flexors are approximately one-third the size of the plantar flexor muscles [TUTTLE, in press b].

In contrast with the leg, the muscles of the forearm evidence few differences between *Pongo* and *Pan*. The large-bodied apes are approximately equal to one another in the relative development of all major functional groups of antebrachial muscles, with the possible exception of the flexor and extensor muscles of the wrist (fig. 28). Whereas the African apes exhibit a predominance of wrist flexors over wrist extensors, the orangutan has a more nearly equal balance in the development of these two groups of muscles.

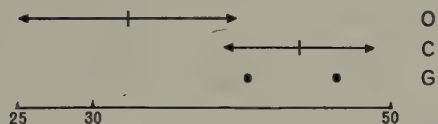


Fig. 26. Ratio expressing the relative weight of the plantar flexor muscles as a percentage of total leg musculature in the Pongidae (symbols as in fig. 23).



Fig. 27. Ratio expressing the relative weight of the extrinsic digital flexor muscles of the foot as a percentage of total leg musculature in the Pongidae (symbols as in fig. 23).

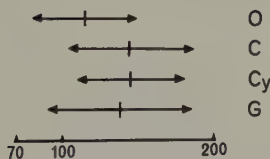


Fig. 28. Ratio expressing the relative weight of the proper wrist flexors as a percentage of the proper wrist extensor muscles in the Pongidae. (O, *Pongo pygmaeus*; C, adult *Pan troglodytes*; Cy, young *Pan troglodytes*; G, *Pan gorilla*; vertical bars, mean values; double-tipped arrows, 90% limits.)

In the Pongidae, the intrinsic muscles of the foot are more markedly contrasted quantitatively than the intrinsic muscles of the hand. For instance, chimpanzees, gorillas, and orangutans have almost equal development of total intrinsic thumb muscles (fig. 29) while the total masses of the intrinsic hallucal flexor and adductor muscles are highly significantly different between the African apes and orangutans (fig. 30).

Similarly, the African apes are different from orangutans more markedly in the relative development of the total mass of pedal lumbrical and interosseous muscles (fig. 31) than in the relative development of total palm muscles (fig. 32). Further, gorillas are more widely disparate from chimpanzees in the relative development of the pedal lumbrical and interosseous muscles than palm muscles (fig. 31 and 32).

In *Pan gorilla*, the total mass of the palm muscles is more than two times the relative mass of the pedal lumbrical and interosseous muscles (fig. 33). By contrast, *Pongo* has nearly equal development of the total mass of the manual and pedal lumbrical and interosseous muscles. *Pan troglodytes* is virtually midway between *Pongo* and *Pan gorilla* in relative development of these muscle groups (fig. 33).

Whereas among the great apes, gorillas evidence the greatest emphasis on manual versus pedal lumbrical and interosseous muscles, chimpanzees exhibit the greatest emphasis on relative development of the hallucal versus pollical intrinsic muscles (fig. 34). In *Pan troglodytes*, the total mass of the short hallucal flexor, abductor and adductor muscles is more than three times the mass of the short pollical flexor, abductor, and adductor muscles. In *Pongo*, the hallucal intrinsic muscles are approximately two times the size of the pollical intrinsic muscles. *Pan gorilla* is intermediate between *Pan troglodytes* and *Pongo* in this feature (fig. 34).

The intertaxonal differences demonstrated in figure 34 are probably mainly due to disparate developments in the hallux more than in the pollex among the three species. Recall that the mean dimensions of the intrinsic

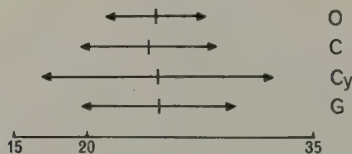


Fig. 29. Ratio expressing the relative weight of total intrinsic thumb muscles as a percentage of total intrinsic hand muscles in the Pongidae (symbols as in fig. 28).

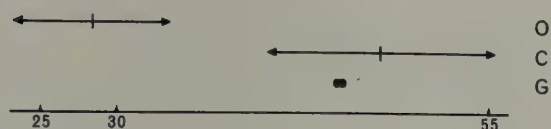


Fig. 30. Ratio expressing the relative weight of total intrinsic flexor, abductor, and adductor muscles as a percentage of total intrinsic foot musculature in the Pongidae (symbols as in fig. 23).

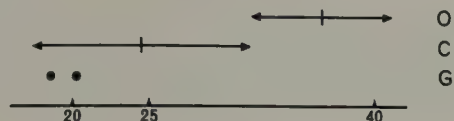


Fig. 31. Ratio expressing the relative weight of the lumbrical and interosseous muscles of the foot as a percentage of total pedal intrinsic musculature in the Pongidae (symbols as in fig. 23).

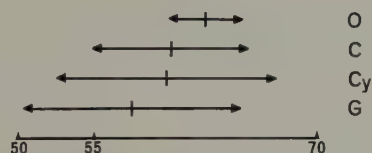


Fig. 32. Ratio expressing the relative weight of the total palm muscles as a percentage of total intrinsic hand musculature in the Pongidae (symbols as in fig. 28).

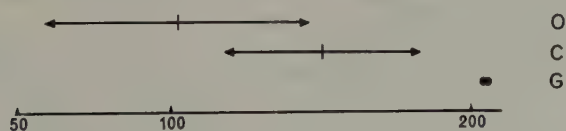


Fig. 33. Ratio expressing the relative weight of the total palm muscles as a percentage of total lumbrical and interosseous muscles in the foot in the Pongidae (symbols as in fig. 23).

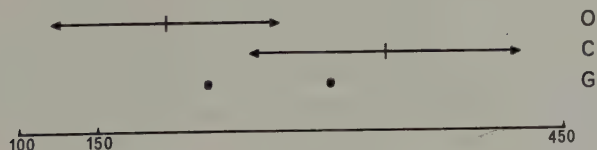


Fig. 34. Ratio expressing the relative weight of total hallucal intrinsic flexor, abductor and adductor muscles as a percentage of total intrinsic muscles of the thumb in the Pongidae (symbols as in fig. 23).



pollical muscles (fig. 29) are much closer to one another than are the mean dimensions of the intrinsic hallucal muscles (fig. 30).

Among the Pongidae, *Pan troglodytes* exhibits greatest and *Pongo* least relative development of the intrinsic muscles that are preaxial to pedal digit III by comparison with the intrinsic muscles that are postaxial to digit III (fig. 35). *Pan gorilla* is approximately midway between *Pan troglodytes* and *Pongo* in relative development of intrinsic pre- and postaxial pedal muscles (fig. 35).

Further, in figure 36 it is illustrated that in *Pan troglodytes* the relative mass of the pedal preaxial intrinsic muscles is approximately 1.8 times that of the manual preaxial intrinsic muscles. *Pan gorilla* and *Pongo* are closely similar to one another and are quite disparate from *Pan troglodytes* in exhibiting less development of the pedal versus manual preaxial intrinsic muscles (fig. 36).

When the pedal postaxial intrinsic muscles are compared with the manual postaxial intrinsic muscles, *Pongo* exhibits a greater development of the former group while *Pan troglodytes* and *Pan gorilla* evidence a greater relative mass of the latter groups of muscles (fig. 37).

The great apes exhibit intertaxonal variations not only in the relative mass of major muscle groups but also in the attachments and fasciculation of individual cheiridial muscles.

In *Pan gorilla*, as in *Pan troglodytes*, the tendons of the long digital flexor muscles of the hand are shortened to the extent that the flexed fingers cannot be opened when the wrist is slightly dorsiflexed. In *Pongo*, by contrast, the fingers commonly may be extended fully while the passive hand is held in maximal dorsiflexion [TUTTLE, 1967]. In some orangutans that have 'fist-walked' habitually and that have had little opportunity to climb in captivity, the long digital flexor tendons may shorten secondarily and thus limit extension of the fingers [TUTTLE, 1969]. However, those animals that have elected 'palmigrade' modes of locomotion in captivity may retain into adulthood the capacity to fully extend the fingers while the hand is 80 to 90 degrees in dorsiflexion [TUTTLE, 1969].

Orangutans, like the African apes, exhibit notable fasciculation of the extensor digitorum and flexor digitorum superficialis and profundus muscles, as well as independent control of the digits. These features enable *Pongo* not only to manipulate objects with a high degree of precision but also to adjust their posturing and grip in terminal branches without necessarily opening the whole hand.

The muscles of the thumb evidence notable differences among the Pongidae. STRAUS [1942, p. 236] concluded that the 'long flexor tendon of the

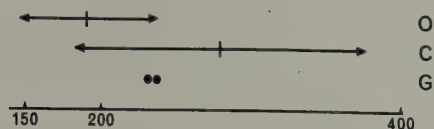


Fig. 35. Ratio expressing the relative weight of intrinsic pedal muscles preaxial to digit III as a percentage of total intrinsic pedal muscles postaxial to digit III in the Pongidae (symbols as in fig. 23).

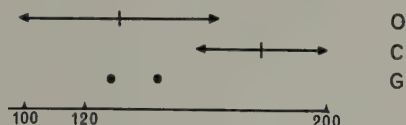


Fig. 36. Ratio expressing the relative weight of total pedal intrinsic muscles preaxial to digit III as a percentage of total manual intrinsic muscles preaxial to digit III in the Pongidae (symbols as in fig. 23).

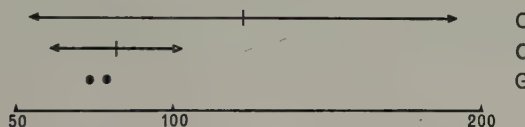


Fig. 37. Ratio expressing the relative weight of total pedal intrinsic muscles postaxial to digit III as a percentage of total manual intrinsic muscles postaxial to digit III in the Pongidae (symbols as in fig. 23).

thumb normally is eliminated physiologically' in 96% of orangutans, 72% of gorillas, and 52% of chimpanzees. The long flexor tendon was totally absent in one and vestigial in six of the seven gorillas that I have dissected. In two of the gorilla specimens the vestigial tendon was fused proximally with the fascia lining the floor of the carpal tunnel. In the remaining four specimens, the vestigial tendon was dispersed proximally in the fascia surrounding the long flexor tendons to digits II-V.

The long pollical flexor tendon was totally absent in the nine orangutans dissected. But in *Pongo*, as in *Pan troglodytes*, the long flexor tendon is replaced by tendinous extensions from the adductor pollicis and flexor pollicis brevis muscles to the distal phalanx. Some authors [e.g. LANGER, 1879, and DAY and NAPIER, 1963, p. 126] have considered this complex of tendons in *Pongo* to be the 'flexor pollicis longus'. However, STRAUS [1942, p. 236] was probably correct in stating that homology with the flexor pollicis longus is highly unlikely. Instead, as the long flexor tendon atrophied due

to a shift of its musculature to supply digit II, the pollical tendon probably developed anew from the intrinsic pollical muscles in response to selective biases for proficient manipulatory capabilities.

Perhaps the most convincing evidence against the proposal that the short pollical flexor tendon is homologous with the 'flexor pollicis longus' is the presence of tendinous extensions from the adductor pollicis and flexor pollicis brevis muscles *in addition to* vestigial long flexor tendons in the hands of some gorillas and chimpanzees (fig. 12). Further, in some gorillas the attachment of the adductor pollicis muscle to the base of the distal phalanx is fleshy, thus evincing advanced distal migration of the intrinsic musculature.

The extensors of the thumb generally are less well developed in *Pongo* than in *Pan troglodytes* and *Pan gorilla* (fig. 38). The difference between orangutans and chimpanzees in relative mass of the pollical extensor muscles is significant statistically but the difference between orangutans and gorillas is not ( $p = 0.05-0.10$ ). The major difference between the pollical extensor muscles in gorillas and the other pongids is the frequent presence of a tendon to the proximal phalanx in the former. The so-called extensor pollicis brevis muscle of *Pan gorilla* was merely a distal extension of the *tendon* of the abductor pollicis longus muscle in specimens that I have dissected. An 'extensor pollicis brevis' did not exist as an entity in those animals since the tendon and associated musculature could only be artificially separated from the abductor pollicis longus muscle. Thus the extensor tendon to the proximal phalanx probably does not exert independent action on the pollex, but instead acts with the abductor pollicis longus muscle to move the thumb as a unit at the carpometacarpal joint.

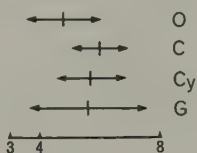


Fig. 38. Ratio expressing the relative weight of the pollical extensor muscles as a percentage of total forearm muscles in the Pongidae (symbols as in fig. 28).

The major differences in attachments of the foot musculature in the three great apes are associated with differential size and usage of the halluces. Chimpanzees and gorillas possess in common a pattern of hallucal musculature that is distinct from that of orangutans. In the African apes, the distal phalanx of the hallux is broad and a powerful tendon from the flexor digi-

torum fibularis muscle attaches to a prominent excavation on its ventral aspect. In orangutans, by contrast, a long flexor tendon is almost always entirely absent [STRAUS, 1942, p. 231]. The long hallucal flexor tendon was absent in the nine specimens of *Pongo* that I dissected. However, as in the hand, the intrinsic pedal muscles send a tendon to the distal phalanx, if present, or to the shaft or distal extremity of the proximal phalanx in animals that lack the distal phalanx. Generally a common tendon to the distal extremity of the hallux emerges from the adductor hallucis, flexor hallucis brevis and abductor hallucis brevis muscles (fig. 39).

In chimpanzees and gorillas, the intrinsic hallucal muscles, particularly the adductor hallucis, also frequently possess a common tendinous extension to the distal phalanx. In the feet of gorillas, as in their hands, the extension of the intrinsic muscles to the first distal phalanx is often fleshy.

Despite the congenital reduction of the hallux in *Pongo*, the peroneus longus and 'abductor hallucis longus' muscles are well developed and have prominent attachments to the base of the first metatarsal bone as in *Pan troglodytes* and *Pan gorilla*. Thus, the halluces of *Pongo* are fully capable of

Fig. 39. Plantar view of a fresh preparation of a right foot of *Pongo pygmaeus*.

The adductor hallucis (ah), flexor hallucis brevis (fhb), and abductor hallucis brevis (ahb) muscles contribute to a common tendon (t) which inserts to the distal phalanx. The pedal lumbrical muscles (l) and flexor digitorum brevis muscle (fdb) also are exposed (photograph by F. KIERNAN, Yerkes Regional Primate Research Center).





flexion and extension as a unit at the tarsometatarsal joint but they probably lack the power of grip exhibited by chimpanzees, western gorillas, and perhaps also eastern gorillas.

#### *D. Summary and Overview*

Comparisons of chimpanzees with advanced terrestrial (gorillas) and specialized arboreal (orangutan) apes not only elucidate the arboreal-terrestrial and locomotion-manipulation compromises in the cheiridia of the former but also reveal unique features in the adaptive complex of each taxon. Chimpanzees share with gorillas anatomical structures that are specially adapted to knuckle-walking and plantigrade posturing of the hands and feet, respectively. In many cases, these anatomical features are somewhat more prominent or advanced in the cheiridia of gorillas than chimpanzees.

Accordingly, the following features may be considered basic components of the knuckle-walking complex in the hands of the African apes: (a) typical friction skin ('knuckle pads') on the dorsal surfaces of the middle phalanges, (b) configuration of the carpal bones and distal radius which act in co-ordination with powerful palmar carpal ligaments to effect close-packed positions in the wrist and thus maintain its integrity against dorsal, lateral, and medial displacements, (c) predominance of wrist flexor in comparison with wrist extensor muscles, (d) extension of the distal articular surfaces onto the dorsal aspects of metacarpal bones II-V, thus permitting marked hyperextension of the proximal phalanges, (e) transverse ridges on the dorsal aspects of metacarpal bones II-V that assist to effect close-packed hyperextended positions of the proximal phalanges, (f) shortening of the tendons of the long digital flexor muscles which subserve essential stabilizing functions at the wrist and metacarpophalangeal joint and that may also provide supplementary propulsive forces at the distal extremity of the forelimb during active posturing, and (g) massive development of the lumbrical and interosseous muscles, the distal attachments of which probably enable them to apply supplementary propulsive forces against the substrate toward the end of the stance phase of the forelimb stride.

In general, gorillas are distinguished from chimpanzees more in hindlimb than forelimb structure, particularly in those features that are related to terrestrial versus arboreal habitus. Gorillas possess nearly equal development of total extrinsic and intrinsic hand versus foot muscles whereas chimpanzees have greater development of total foot musculature. This may

be related to the fact that chimpanzees utilize the hindlimbs more frequently for climbing trees while gorillas use the four limbs in more equal frequencies for quadrupedal locomotion.

The external configuration of the foot in *Pan gorilla*, with its massive heel, interdigital webbing, and short second to fifth toes, indicates advanced plantigrady compared with the foot of *Pan troglodytes*.

Although the plantar flexor muscles are not better developed relative to other groups of leg muscles in gorillas compared with chimpanzees, they act on a much longer 'power-arm' in the former. In gorillas, as in chimpanzees, this heel-raising mechanism may be used advantageously both in climbing trees and terrestrial locomotion due to the presence of a flexible transverse tarsal joint that permits the elevation of the heel while the digits grasp or rest on the substratum.

The extensive interdigital webbing in the foot of gorilla serves as a functional extension of the sole distally. But since the hallux is also implicated by the webbing, abduction of the first digit and concordantly prehensility of the foot are reduced, especially in eastern mountain gorillas.

The apparent shortening of pedal digits II–V and the increased webbing of the hallux to the remaining digits has not been accompanied by marked reductions in the extrinsic digital flexor muscles in the feet of available gorillas by comparison with chimpanzees. However, the intrinsic muscles of the foot, especially the lumbricals and interossei, are notably less developed in the feet of gorillas than chimpanzees when these muscles are compared with the palm muscles. The intrinsic hallucal muscles of gorillas are well developed but not to the extent exhibited in chimpanzees.

The cheiridia of *Pongo* are fundamentally adapted for four-digit suspensory posturing and locomotion. Although chimpanzees share with orangutans some features of the hand that may be related to proficient suspensory posturing, viz. elongation and palmar curvature of the second to fifth manual rays and the 'double-locking' mechanism of the fingers, the feet of chimpanzees exhibit virtually no features that may be correlated with a special four-digit suspensory grasp of the sort common to orangutans.

The relative mass of most muscle groups in the forearms and hands of *Pan* and *Pongo* are closely similar. However, orangutans are distinct from the African apes in possessing nearly equal balances of wrist flexor and extensor muscles [TUTTLE, 1969 and b] and perhaps also in having less development of the extrinsic pollical extensor muscles.

In *Pongo*, by comparison with *Pan*, the total musculature of the leg and foot is considerably smaller than the muscles of the antebrachium and hand.

Further, in contrast with muscles of the hand, most muscle groups in the leg and foot of *Pongo* are markedly different in relative mass from those of *Pan*.

In *Pongo*, the extrinsic flexor muscles act only on pedal digits II–V and they are nearly as massive as the plantar flexor muscles. In addition, the pedal lumbrical and interosseous muscles are developed in *Pongo* to a greater extent than in *Pan*. There is a trend toward more equal development of pedal and manual lumbrical and interosseous muscles in *Pongo*. These emphases on extrinsic and intrinsic flexor muscles of pedal digits II–V correlate with the pre-eminence of four-digit suspensory supporting as compared with other functions of the orangutan foot.

Additional features in pedal cheiridia of *Pongo* that may be related to special suspensory posturing include (a) marked permanent suspinsion of the foot, (b) the ‘double-locking’ mechanism in the lateral four toes, (c) limited extension and permanent flexion set of the metatarsophalangeal and interphalangeal joints, and (d) special elongation and plantar curvature of the second to fifth rays. These features combine to give the feet of orangutans a ‘hook-like’ appearance not unlike their hands. This often leads to difficulty in discerning manual from pedal cheiridia in *Pongo*.

The mechanical demands of suspensory posturing in chimpanzees and orangutans and perhaps also knuckle-walking posturing in the African apes, are associated with morphological compromises between manipulative and locomotive functions of the hands. Although the pollex is a proficient manipulatory organ in the Pongidae, it bears notable evidence of a functional shift of emphasis from digit I to digits II–V. Accordingly, the extrinsic digital flexor muscles have null action on the pollical distal phalanx due to the absence or vestigial condition of the long pollical flexor tendon. Reduction of the long flexor tendon to the thumb is most marked in *Pongo* but it is characteristic also of *Pan troglodytes* and *Pan gorilla*.

The absence of a functional long flexor tendon in the thumbs of the great apes is partially compensated by tendinous extensions from the intrinsic muscles of the thumb to the distal pollical phalanx. The intrinsic pollical muscles constitute approximately the same relative mass in *Pongo* and *Pan*; but in each species these muscles exhibit unique attachments, fasciculation, or both. *Pongo* possess an elaborate proliferation of intrinsic thumb muscles, many of which attach to the distal phalanx by a complex of fine tendons. *Pan gorilla* differs from other species of the Pongidae in sometimes possessing a fleshy extension from the intrinsic pollical muscles to the distal phalanx. The intrinsic pollical muscles not only co-ordinate actions of the distal phalanx with the remainder of the first ray but also probably are responsible for

subtle excursions of the thumb as a unit at the carpometacarpal joint during refined manipulatory actions.

The prehensile capabilities of the hallux vary widely between *Pan* and *Pongo* because of its robustness in the former and its remarkable congenital reduction in the latter.

In the African apes, the hallucal distal phalanx is broad and flat and it is supplied by a stout tendon from the flexor digitorum fibularis muscle. By contrast, in the orangutan, the hallux typically lacks not only the long flexor tendon (94 % of specimens) but also the terminal phalanx and nail (more than 60 % of specimens).

But, as in the hand, the phalanges of the reduced first pedal digit receive tendinous extensions from the intrinsic muscles in *Pongo*. Similarly, the halluces of *Pan* commonly possess tendinous (*P. troglodytes*, *P. gorilla*) or fleshy (*P. gorilla*) extensions from the intrinsic hallucal muscles to the distal phalanx even though they evidence no tendency for reduction of the long flexor tendons.

In *Pongo*, the intrinsic hallucal muscles are absolutely large and thus provide the diminutive digit with some prehensility. Further, the peroneus longus muscle is attached so as to flex the hallux as a unit at the tarsometatarsal joint. But compared with the halluces of *Pan*, those of *Pongo* are poorly supplied with muscles.

## VIII. EVOLUTIONARY TRENDS

### *A. Introduction*

Several questions may be raised regarding the evolutionary history of the special features exhibited in the cheiridia of the extant Pongidae. What selective biases in the arboreal and terrestrial environments of the African apes led to the knuckle-walking complex in their hands? To what extent were the hands of the African apes adapted to suspensory posturing prior to the adaptive shift to knuckle-walking?<sup>3</sup> Was the common ancestor of chimpanzees

3 The elucidation of this question is pertinent to resolving current differences of opinion on the course of human evolution. WASHBURN [1967; 1968], a persistent 'brachiationist' has recently proposed that the progenitors of man were 'knuckle-walkers' before they became 'bipeds'. On the basis of morphological and behavioral evidence from the hands of extant apes and man, TUTTLE [1965, 1967] has stated that such an evolutionary pathway is highly improbable because it requires remarkable reversals in relatively short periods of time. PILBEAM [1968] also considers this theory of WASHBURN to be unreasonable and states that it is not supported by available fossil evidence.



and gorillas a 'knuckle-walker' or did knuckle-walking develop in parallel in the two forms? What selective biases in the environments of orangutans led to the advancement and culmination of special four-digit suspensory habitus in their hands and feet? Were the cheiridia in the common ancestors of orangutans and the African apes specially adapted for four-digit suspensory posturing? What selective factors led to the greater reduction of the hallux as compared with the pollex in *Pongo*? What factors in the environments of the African apes maintained and advanced the hallux as a prehensile organ? When did the three great apes diverge from one another?

Ideally, these questions might be answered by careful examination of accurately dated series of fossil cheiridia, the faunal and floral associations of which were well documented, and the functional capabilities of which were clearly discernible. But the fossil record of the Pongidae is impoverished in postcranial remains that might elucidate cheiridial evolution and modern techniques that may permit the inference of specific locomotor modes from available fossil remains are only currently being developed.

Thus, in the following discussion, fossil evidence and results from comparative morphological studies on the extant apes will be utilized to infer answers to questions on the evolution of the great apes. Since definite conclusions cannot be drawn on the basis of available knowledge, nearly all statements must be considered as more or less carefully reasoned speculations.<sup>4</sup>

### B. Fossil Hands and Feet

In Tertiary and Pleistocene deposits, remains of cheiridia have been found in close association with cranial remains of *Dryopithecus* (*Proconsul*) *africanus*, *Pliopithecus* (*Epipliopithecus*) *vindobonensis*, *Limnopithecus macinnesi*, *Oreopithecus bambolii*, and the Olduvai and Swartkrans Hominoidea. Additional remains have been recovered in East Africa recently, but systematic descriptions of them are not available.

Only the remains of *Dryopithecus* (*Proconsul*) *africanus* and perhaps also

4 Statements on the evolution of hominoid cheiridia are necessarily tentative because refined experimental techniques and further comparative anatomical and behavioral studies have been initiated only recently by OXNARD and TUTTLE at the University of Chicago. And, more importantly, the recent intensification of paleontological research by the LEAKEYS, HOWELL, ARAMBOURG, PATTERSON and others in East Africa, and SIMONS and his colleagues in North India may provide new fossil evidence that would pertain directly to the evolution of the African apes.

*Dryopithecus (Proconsul) nyanzae* may have direct relevance to the evolution of hands and feet in the Pongidae since the other available fossils are assigned to the Hylobatidae (or Pliopithecidae), Oreopithecidae, and Hominidae.

Although the general proportions of the carpal, metacarpal, and third digital segments of the hand of *Dryopithecus africanus* are closely similar to those of *Pan troglodytes* [NAPIER and DAVIS, 1959], the detailed configuration of the distal extremity of the radius and the individual bones of the hand possess virtually no features of the knuckle-walking complex as exhibited in the hands of the extant African apes [TUTTLE, 1967].

Similarly, according to NAPIER and DAVIS [1959, p.55] the fragmentary foot bones of *Dryopithecus africanus* belonged to 'an arboreal form' and evidently did not possess features clearly related to terrestrial habitus. But as noted in Section V, even though chimpanzees commonly walk on the ground, available studies have failed to reveal features attributable solely to terrestrial plantigrade habitus.

Fossil tali [SONGHOR and RUSINGA ISLAND] and a calcaneus [SONGHOR] have been found in Kenyan Miocene deposits from which dental and other remains of *Dryopithecus (Proconsul) nyanzae* have been recovered [LEGROS CLARK and LEAKEY, 1951]<sup>5</sup>. LEGROS CLARK and LEAKEY [1951, pp.91-92] noted that 'the tarsal elements formed a stronger and more firmly knit mechanism than in the modern large apes' and that 'the anterior tarsal segment had not undergone the shortening which is characteristic of the modern large apes.' LEGROS CLARK and LEAKEY [1951, p.91] concluded that in *D. nyanzae* 'the foot was held in a more everted plantigrade position similar to that of the cercopithecoid foot, and strongly suggests quadrupedal functions on the ground or among the branches of trees.'

In summary, available cheiridial remains of possible ancestral pongids generally do not exhibit special adaptations to terrestrial quadrupedal locomotion. But these remains of the Miocene Pongidae also present no features that would deny terrestrial locomotion as part of their motile activities.

Both the hand and foot of *Dryopithecus (Proconsul) africanus* indicate that it was well adapted to climb in trees. The fossil tarsal bones from Songhor and Rusinga Island, Kenya, indicate more clearly a trend toward terrestri-

5 LEGROS CLARK and LEAKEY [1951, p.87] stated that these fossil foot bones 'are most likely to belong to *P. nyanzae*, partly because of their general dimensions and partly because the remains of this species are the most common. There is one other possibility - that these tarsal bones belong to the species which is here called *Sivapithecus africanus*. However, remains of this type are very rare, and none of them was found in close relationship to the tarsal bones.'

ty, but it is impossible on the basis of available studies to state the relative importance of arboreal versus terrestrial substrates in the foraging and locomotor modes of these hominoids.

### *C. Inferences from Fossil Apes*

The primary criteria whereby a fossil primate may be assigned to the Pongidae are dental characteristics. Although the extant great apes are clearly distinct from the other primates in features of the postcranial skeleton, especially those that are related to suspensory posturing (*Pongo*, *Pan*) and knuckle-walking (*Pan*), available remains indicate that many of these features evolved after pongid trends were well established in the dentition. Thus, attempts to sketch the early stages in the phylogeny of the Pongidae are based heavily on evidence from the teeth and associated cranial morphology and only secondarily on evidence from the postcranium.

In an extensive revision of the Dryopithecinae, SIMONS and PILBEAM [1965] concluded that the hundreds of available specimens of early or middle Miocene-early Pliocene apes may represent only seven species of *Dryopithecus*. SIMONS and PILBEAM [1965, p. 141] further concluded that 'In comparable parts all *Dryopithecus* species are much more similar to each other than are the various African species or races of chimpanzees and of gorillas in the same parts.'

While opinions vary on precisely which of the species of *Dryopithecus* may have been ancestral to the extant African apes, it is generally agreed that chimpanzees and gorillas evolved from early or middle Miocene dryopithecine populations somewhere in Africa. SIMONS and PILBEAM [1965], LEAKEY [1963], and PILBEAM [1968] have suggested that the largest form of *Dryopithecus*, represented by *Dryopithecus (Proconsul) major* in Kenya, the Moroto palate from Uganda [ALLBROOK and BISHOP, 1963], and perhaps also *Dryopithecus (Sivapithecus) indicus* in South Asia, is an excellent candidate for a Miocene ancestor of the gorillas.

By contrast with gorillas, ascertaining the probable ancestor of chimpanzees is somewhat more problematical. SIMONS and PILBEAM [1965] have suggested that either *Dryopithecus (Proconsul) nyanzae* or *Dryopithecus (Dryopithecus) fontani* was ancestral to *Pan* (exclusive of *P. gorilla*). Since they also stated that '*D. fontani* and *D. nyanzae* could possibly represent local populations of one widespread species' [p. 139], it is probable that of the two forms the African one, i.e., *D. nyanzae*, was ancestral to *Pan troglodytes*.

Further studies of the Dryopithecinae, however, have led PILBEAM [1968] to propose still another possible ancestor of living chimpanzees. Thus, PILBEAM [1968, p.1336] stated that '*D. africanus* is now better regarded as a form ancestral to, or close to the ancestry of the chimpanzee, *Pan troglodytes*.'

Pre-Pleistocene orangutans or their ancestors are not discernible among available remains of fossil great apes. The fossil record of the Miocene and Pliocene periods is much less complete in South China and Southeast Asia than in East Africa. Remains of the Dryopithecinae in South Asia, viz. *D. indicus*, *D. sivalensis*, and *D. laietanus*, neither support nor deny the derivation of *Pongo* from populations of one of these species. Accordingly, the time of divergence of ancestral orangutans from ancestral chimpanzees and gorillas cannot be determined on the basis of available fossil evidence.

To summarize, available fossils support the inference that ancestral chimpanzees probably had begun to diverge from ancestral gorillas in early or middle Miocene times. These Miocene apes lacked many of the special morphological features of *Pan troglodytes* and *Pan gorilla*. The phylogenetic origin and development of *Pongo* is undocumented by (or perhaps merely unrecognized among) Tertiary remains.

#### *D. Inferences from Extant Apes*

Three basic kinds of data, derived from the extant apes, may be utilized to infer their taxonomic affinities and evolutionary history. Firstly, comparative morphological studies may reveal similarities from which taxonomic relationships, both among extant forms and between these and fossil forms, may be inferred.

Secondly, comparative behavioral studies may indicate similarities between extant species that corroborate comparative anatomical evidence. In fact, often the main value of behavioral data in evolutionary biological studies is in providing more creative frameworks for the interpretation of the functional significance of morphological features, particularly when comparisons subsequently are made between fossil and extant forms.

Thirdly, certain biomolecular features, as revealed by modern techniques of karyotypology [KLINGER *et al.*, 1963; CHIARELLI, 1962] and serum protein electrophoresis and immunodiffusion [GOODMAN, 1962, 1963 and 1967; WILLIAMS, 1964; SARICH and WILSON, 1967; SARICH, 1968], generally adduce



to the relatively close taxonomic affinities of the living apes, especially the African pongids, and man.

The comparative morphological, behavioral, and biomolecular studies thus increase the reliability and innovation of interpretations of the fossil record. But only the accurately dated fossils themselves may provide a time perspective and confirmation or denial of phylogenetic hypotheses based on syntheses of results from these studies.<sup>6</sup>

With these reservations in mind, the most likely pathway in the evolution of the knuckle-walking complex in *Pan* may be outlined tentatively on the basis of biomechanical considerations of manual function and associated morphology. Accordingly, the knuckle-walking posture probably is the result of a highly effective morphological compromise that was instituted in long-fingered, arboreally adapted apes concomitant with an adaptive shift to terrestrial quadrupedal locomotion. Gorillas and chimpanzees possess many morphological features that indicate that their ancestors were arboreal; and they have remained active climbers. Suspensory posturing may be utilized by chimpanzees in a variety of foraging and feeding contexts and juvenile gorillas sometimes hang by one or both extended forelimbs during play and other motile activities.

There is an ubiquitous trend toward reduction in length of the digits in terrestrial primates. Long digits are not only biomechanically inefficient but also may be maladaptive in many terrestrial contexts. Although most orangutans [TUTTLE, 1967], gibbons [CARPENTER, 1940], spider monkeys [ERIKSON, 1963], and other long-fingered anthropoid primates are capable of fully extending their digits, they rarely do so when forced to move on the ground. Instead they often exhibit a variety of partially flexed or tightly flexed finger postures that permit the hand to be used as a stable supporting prop but with negligible propulsive potentiality. Orangutans rarely utilize fully palmigrade postures on the ground. Further, during rare bouts of palmigrady, they hold the hands *outward* at right angles to the line of progression (fig. 4).

Similarly, when gibbons and spider monkeys walk quadrupedally with

6 Recently, SARICH and WILSON [1967] and SARICH [1968] have attempted to determine the time of divergence of the gibbons, great apes, man and others of the Anthropoidea, by immunological studies of serum albumins. Acceptance of the inferences derived from these studies not only stresses unduly modern concepts of evolutionary rates and the complexity of the genetic substrates underlying phenotypic features but also are often totally unsupported and, in some instances flatly denied, by available fossil evidence.

the fingers fully extended, the hands are held outwards from the sides of the body and are not aligned with the direction of travel. Thus, the digits are not in a position to act effectively as propulsive levers.

Moreover, rapid locomotion might be prohibited on the forest floor by the outwardly projecting hands catching on vegetation and other topographical irregularities of the substratum. Palmigrady is much more effective in progression on a cage floor than the forest floor because few areas of the natural habitat would provide an unobstructed pathway, particularly for large apes like *Pongo*.

Thus, when long-fingered arboreal primates moved to the forest floor, flexed-finger posturing would have permitted them to use their hands as supporting props without danger of catching on surrounding vegetation or stressing digits that were too long to serve as efficient propulsive levers in palmigrade postures.

The development of flexed-finger posturing need not be viewed solely as a terrestrial development, however. Orangutans utilize fist-walking postures in progression atop large branches and to pack down nesting materials (sections II and III). Similarly, the long-fingered ancestors of the African apes may have had some experience with flexed-finger posturing prior to coming to the ground.

Once the trend toward flexed-finger posturing was established, whether in trees or on the ground, selection may have acted to convert the hand from an organ that subserved only supporting functions to one that was more effective in terrestrial propulsion. Elevation of the palm so that the load rested on the dorsum of the middle phalanges and hyperextension of the proximal phalanges at the metacarpophalangeal joints would have positioned the hand so as to provide some supplementary propulsive force at the distal extremity of the forelimb in a manner reminiscent of the 'toe snap' in the human foot.

Other authors [e.g. STRAUS, 1940; JOUFFROY and LESSERTISSEUR, 1960] also have attributed the knuckle-walking habitus in the hands of the African apes to prospective adaptations for arboreal environments in their ancestors. Accordingly, these authors emphasized, perhaps too greatly, the concept of the pongid hand as a fixed 'anatomical hook' for 'brachiation' that could only be used in terrestrial locomotion by apposing the dorsum of the 'hook' to the ground.

Since the shortened long digital flexor tendons and other features that limit hand opening and wrist mobility are markedly developed only in the African apes among pongids, and since these structures are of distinct bio-

mechanical advantage in terrestrial locomotion, it is perhaps best to view them as *de novo* adaptations to knuckle-walking.

Thus, although the hands of the African apes probably evolved from those of long-handed arboreal apes that engaged in climbing and feeding behaviors which traditionally are associated with 'brachiators', the manual cheiridia of these early apes were probably not rigid hooks with permanently flexed fingers and relatively inflexible wrists. Instead, there was probably a period during which the early apes engaged in fist-walking or modified palmigrade posturing before they developed and advanced as knuckle-walkers. Further, once the adaptations to knuckle-walking were advanced in their hands and concordantly when they were of considerable body size, acrobatic arm-swinging, particularly as an effective means of traversing notable distances in the canopy, was probably limited compared with their more arboreal ancestors.

Finally, a totally different and, at present, less tenable hypothesis would consider terrestrial knuckle-walking to be prospectively adaptive to using the hands as arboreal suspensory organs. That is to say, according to this theory the early apes would be considered knuckle-walkers that subsequently became increasingly advanced and specialized for foraging and feeding in trees. Thus, hypothetical hands that were adapted to knuckle-walking would have become progressively more flexible in response to selective biases in arboreal habitats. While the dearth of fossil remains that might directly deny this hypothesis permits it to stand as a possibility, convincing evidence in support of it is neither present among available fossil remains (*viz. Dryopithecus africanus*) nor in results of comparative morphological studies.

Orangutans exhibit virtually no features that reflect knuckle-walking habitus in their phylogeny. Instead, the hands of orangutans are highly advanced as suspensory organs. In addition, the feet of *Pongo* have developed as suspensory organs perhaps to even a greater degree than the hands. The hallux of *Pongo* has been subjected to more extreme reduction than the pollex [STRAUS, 1942]. This unique reduction of the hallux may be viewed as part of a trend that generally affected the first cheiridial rays concomitant with the advancement and subsequent specialization of the remaining four digits of hand and foot for suspensory prehension. The fact that the diminution of the first digit has advanced farther in the foot than hand of *Pongo* may be the result of concurrent selective biases for proficient manipulatory functions in the latter organ [TUTTLE and ROGERS, 1966].

In *Pongo*, as in *Homo*, the foot has been altered radically from the basic pongid pattern [MORTON, 1924] to the extent that pedal structure clearly

denotes divergence of each of these hominoids from *Pan* and from each other. Extreme selective biases for arboreal climbing and clinging appear to have been operative in early populations of orangutans and these have culminated in the unique adaptations of their cheiridia. It is impossible to determine in detail the many environmental factors that may have contributed to this remarkable adaptive complex, but it is possible that among them was the periodic and seasonal flooding of the Sunda Shelf region and concordantly the development of extensive swamp forests which appear to be preferred habitats of orangutans today [TUTTLE, 1968].

Ancestral African apes probably had greater opportunities for terrestrial progression and feeding than ancestral orangutans and perhaps they more frequently exploited resources on the forest floor, in clearings and in forest-savanna boundary areas. Whereas ancestral gorillas became increasingly adapted to forest floor subsistence patterns, ancestral chimpanzees remained arboreal in feeding and nesting activities.

The large size of gorillas probably developed during the shift to terrestrial habitation and eventually forced them to nest more frequently on the ground. Gorillas probably did not achieve their prodigious bulk in trees, thus being forced to come to the ground. Instead their enormous size probably developed as part of a terrestrial foraging-feeding and defensive complex which enables them to exploit food resources in the shrub layer of vegetation.

Unlike *Pongo*, the special adaptations of *Pan* to the major locomotor substratum has affected the hands more evidently than the feet. Although the feet of chimpanzees and particularly gorillas are well adapted to terrestrial plantigrade locomotion, they have not been radically altered from the basic anthropoid ape pattern. By contrast with their feet, the hands of the African apes have become uniquely adapted to quadrupedal terrestrial locomotion.

The most parsimonious hypothesis on the development of the knuckle-walking complex would consider chimpanzees and gorillas to have diverged rather recently from a hypothetical knuckle-walking ape that in turn had developed from a long-handed arboreal ancestor. This hypothesis is favored in the absence of *postcranial* remains that would support the parallel development of knuckle-walking in chimpanzees and gorillas immediately after divergence from a common arboreal ancestor. If this hypothesis is in fact a true representation of the phylogeny of chimpanzees and gorillas then the taxonomy of these apes should reflect their close common ancestry [TUTTLE, 1967]. On the other hand, if parallel evolution of the knuckle-walking complex is documented by future fossil discoveries, chimpanzees and gorillas



probably should not be considered congeneric as has been suggested by recent authors [MAYR, 1950; SIMPSON, 1963; WASHBURN and HAMBURG, 1965; BUETTNER-JANUSCH, 1966; TUTTLE, 1967].

### *E. Summary and Overview*

Many of the questions raised in Section VII. A. cannot be answered certainly on the basis of available paleontological, comparative morphological, behavioral, and biomolecular evidence.

On the basis of behavioral and functional morphological evidence, living orangutans (*Pongo*) and the African apes (*Pan*) probably represent the culmination of a 'dichotomous pattern' [GRANT, 1963, pp. 452-453] of evolution from an unknown ancestral population. Because of the virtual absence of any recognized fossil remains of pre-Pleistocene orangutans, the time of divergence of the two pongid lines could lie anywhere between Oligocene and Pliocene times. Further, the extent to which the common ancestor of *Pongo* and *Pan* was specially adapted to suspensory posturing and arm-swinging prior to divergence and speciation is not known. It is quite possible that adaptations to suspensory posturing and locomotion developed in parallel in the two lines. Parallel adaptations to 'brachiation' have been documented in at least two other lines of the Anthropeidea, viz. *Oreopithecus*, the Atelelinae, and perhaps also the Hylobatidae.

Finally, although the fluctuations of the sea level and periodic flooding of the Sunda Shelf during the Pleistocene may have contributed to the culmination of trends toward special suspensory prehensile mechanisms in *Pongo*, this is almost certainly not the only selective complex responsible for its special adaptive mode. Furthermore, Pleistocene climatic factors probably are not responsible for the initial divergence of orangutans from the ancestors of the African apes. Instead the initial separation was due perhaps to the differences in foraging and feeding behaviors.

The divergence of chimpanzees and gorillas, in contrast with their separation from orangutans, probably followed an 'excurrent pattern' [GRANT, 1963, pp. 452-453] of evolution. That is to say, although gorillas are decidedly different from chimpanzees in a number of features, e.g., external genitalia, dentition, and alimentary tract, the common chimpanzee is probably an excellent basic model of the ancestral species from which living chimpanzees and gorillas evolved.

If odontological evidence in the fossil record is considered alone, the

divergence of chimpanzees and gorillas may be dated before or during Miocene times. Further, postcranial remains associated with the fossils upon which this inference is based indicate that gorillas and chimpanzees probably speciated not only before they acquired knuckle-walking adaptations but also before they developed the limb proportions and other special features of advanced 'brachiators'.

But until more complete postcranial remains are found in association with the larger species of *Dryopithecus* and until the phylogenies of chimpanzees and gorillas can be less equivocally traced to particular populations of *Dryopithecus* the common origin of *Pan troglodytes* and *Pan gorilla* from a knuckle-walking ancestor (that, in turn, originally had developed special adaptations to arboreal foraging and feeding) cannot be denied. Thus, the most parsimonious inference that may be drawn from the functional morphological evidence indicates a date of divergence of the species of African apes somewhat later than middle Miocene. But again, we must await future paleontological and further biomechanical discoveries in order to finally resolve this fascinating problem.

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Author's address: RUSSELL H. TUTTLE, Department of Anthropology, 1025 E. 57th St., University of Chicago, Chicago, IL 60637 (USA).

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# THE CHROMOSOMES OF THE CHIMPANZEE

B. CHIARELLI

Centre of Primatology, Institute of Anthropology, University of Turin

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## INTRODUCTION

The interest in the study of the chromosomes of a certain species resides in the fact that these structures contain the genetic information responsible for the features of each individual and for the general characteristics of the species. How the genetic information is organized in the chromosomes and how it works and expresses itself, is far from well known at least in the case of chromosomes of higher mammals and only some preliminary scheme and suggestions have been recently proposed [DU PRAW, 1966; URSPRUNG *et al.*, 1968]. In the nucleus of a mammalian cell during the interphase a structurized chromosome is not visible.

The chromosomes as independent structures are clearly recognizable in the cell only during the mitotic and meiotic division. During the process of mitosis, from the nuclear matrix, a sort of threadlike filament becomes visible. During the prophase these threads become shorter and thicker and hence appear to be more deeply stained.

At the end of prophase they are more aptly described as short rods: the chromosomes. They are composed of two stands which are called chromatids and both contain exactly the same genetic material in the same configuration.

During the following stages, they continue to contract and the two chromatids of each chromosome separate from each other along their length, but remain connected to each other at one point: the centromere which may be in any position along the length of chromosome but is in a fixed position in each chromosome.

The number, the dimensions and the position of the centromere of each chromosome are almost constant characteristics of every cell of all the individuals of the same species. On the other hand, different species of the same taxonomic group may present a different number of chromosomes or differences in their morphology.

This stability and uniformity in the chromosome number and morphology is assured by the meiotic process, which tends to eliminate any change or mutation in the organization of the genetic information on them.

For this reason, almost all the mutations which could occur spontaneously (such as chromosome rearrangements or deletions) are abortive; only few survive with the cell which carries them in the soma of the individual.

Occasionally some change can pass through the sieve of meiosis and be transmitted to the descendant. In this case it can be eliminated by natural selection or assimilated as a new characteristic of the caryotype of the species.

The spread and the establishment of such a change would be more rapid if mutations with a certain selective advantage are superimposed on these structural changes. For this reason a detailed study of the chromosomes of a certain species gives reliable information in characterizing a species and for the study of the processes and mechanisms of the evolution of a taxonomic group.

The chromosomes of the primates are probably the most extensively studied among the mammals. A synthesis of the available data for the Old World primates has been recently published [CHIARELLI, 1968].

The chimpanzee particularly was one of the first to be studied for the point of view of the chromosomes. In fact it was in 1940 that YEAGER *et al.* obtained a count of  $2n = 48$ , from spermatogonial metaphases from a specimen of *Pan troglodytes*.

In 1960 YOUNG *et al.* using bone marrow cells, confirmed this number on nine animals. They tentatively identified the X as a moderately large metacentric and the Y as a small metacentric. Since that time many other animals have been studied (table I) and a number of  $2n = 48$  chromosomes has been always confirmed (fig. 1).



Table I. Chimpanzee studied for the chromosomes

Species	No. of specimen and sex		References
	♂	♀	
<i>P. troglodytes</i>	1	—	YEAGER <i>et al.</i> , 1940
<i>P. troglodytes</i>	7	2	YOUNG <i>et al.</i> , 1960
<i>P. troglodytes</i>	2	5	CHU <i>et al.</i> , 1961, BENDER <i>et al.</i> , 1963
<i>P. troglodytes</i>	2	2	CHIARELLI, 1962
<i>P. troglodytes</i>	1	2	HAMERTON, 1963; HAMERTON <i>et al.</i> , 1963
<i>P. paniscus</i>	1	—	CHIARELLI, 1962
<i>P. paniscus</i>	1	2	HAMERTON, 1963; HAMERTON <i>et al.</i> , 1963

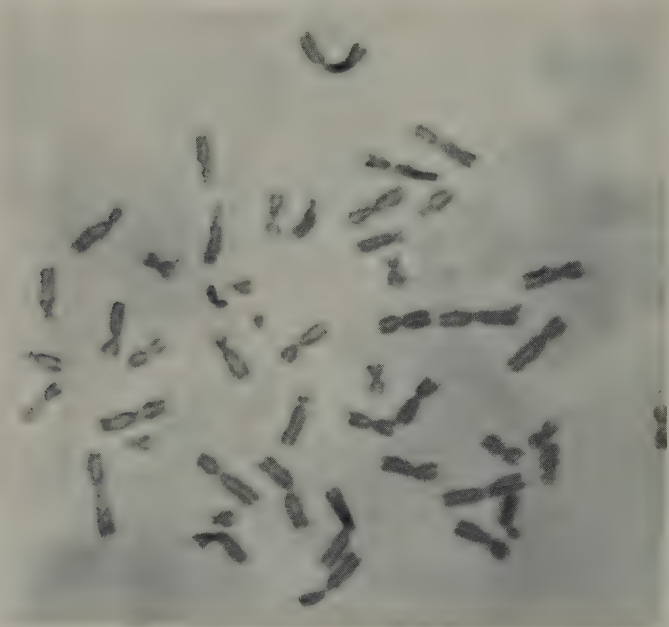


Fig. 1. A metaphasis plate of the chromosomes of a male *Pan troglodytes*.

MORPHOLOGICAL DATA OF THE CHIMPANZEE CARYOTYPE

Detailed information on the caryotype of the chimpanzee is available. In the morphometric analysis developed by CHIARELLI [1962], the 48 somatic chromosomes of the chimpanzee were subdivided into 5 groups of autosomes of similar shape and into one pair of sex chromosomes.

Figure 2 shows the reconstruction in pairs of the chromosomes of a male of *Pan troglodytes*. The arrangements in pairs were made on the basis of a morphological judgement, although metric control was always performed using direct or relative measurements and indices. The homologous chromosomes are arranged as far as possible in decreasing order of size.

The first group contains the five longest pairs of chromosomes. They are arranged in decreasing order of size. Chromosomes 1, 2 and 4 are metacentric. Chromosomes 3 and 5 are submetacentric.

The second group contains six medium-sized pairs of chromosomes all meta- or submetacentric.

The third group contains six pairs of chromosomes submetacentric (chromosomes 12 and 13) or telocentric. They are also arranged in decreasing order of size.

The fourth group contains four chromosomes of small size. They are all metacentric.

The fifth group contains two pairs of chromosomes of small size. Because of the position of the centromere they must be classified as acrocentric. They seem to have an achromatic zone in the short arm.

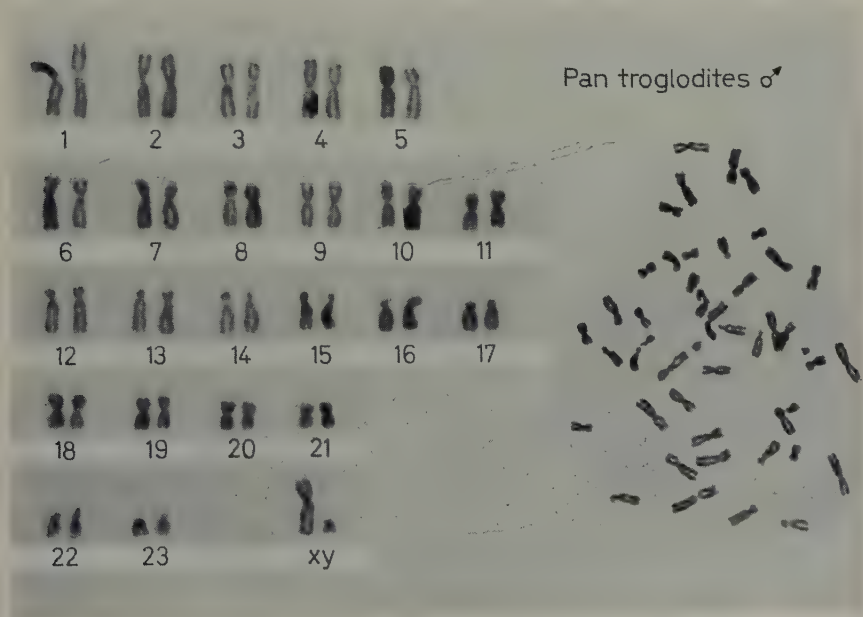


Fig. 2. Metaphase plate and reconstruction in pairs of the chromosomes of a male *Pan troglodytes*.

With regard to the sex chromosomes, whereas the Y chromosome is easily recognizable, the X presents some problems. The Y chromosome is one of the smallest of the set and is entirely euchromatic. The position of the centromere here could be classified as submetacentric. The X chromosome chosen by exclusion in pairing the autosomes is one of the largest, very similar to chromosome 3 or 4.

Figure 3 shows the reconstruction in pairs of the chromosomes of a male *Pan paniscus*. The chromosomes of *Pan paniscus* differ from those of *Pan troglodytes* in the chromosomes 12, 22 and 23 which have their centromeres in a more metacentric position. These differences could be due to mutation events of the type of the inversion. A similar analysis developed some time later by HAMERTON *et al.* [1963], on other specimens, reached practically identical conclusions. More recently, and at the moment not yet published, a detailed study for the identification of the chromosome pairs of the chimpanzee has been undertaken by K. BENIRSCHKE using tritiated thymidine.

Figure 4 presents a selected haploid set of the chromosomes obtained at high magnification from one plate of a male *Pan troglodytes*. Several detailed characteristics of the chromosomes of this species can be noticed. So far no

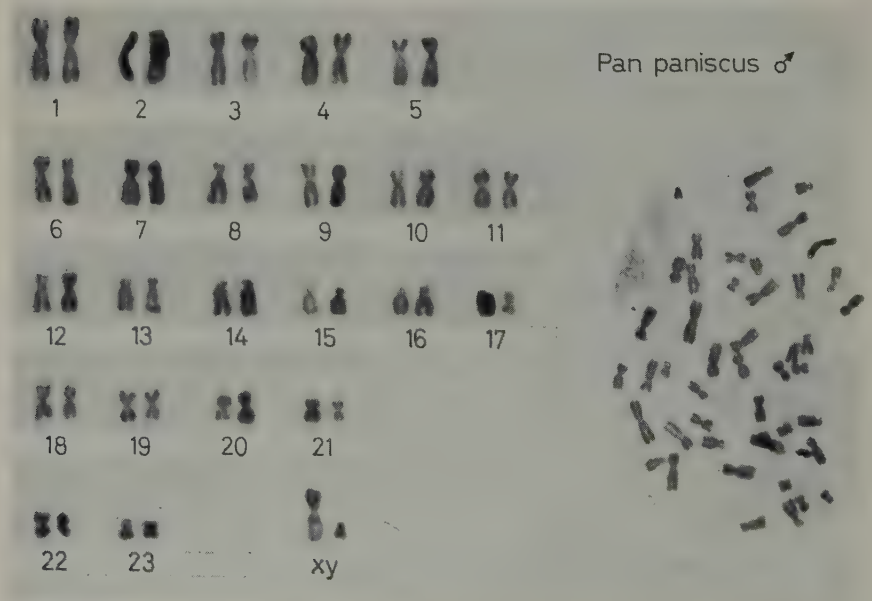


Fig. 3. Metaphase plate and reconstruction in pairs of the chromosomes of a male *Pan paniscus*.

information is available on the meiotic chromosomes. This type of information, when obtained, will enrich our knowledge on the cytogenetic of the chimpanzee and will allow a deeper and more extensive comparison with caryotype of other non-human primates and of man for which data on the meiotic chromosomes are available [CHIARELLI *et al.*, 1967; FALEK *et al.*, 1968].

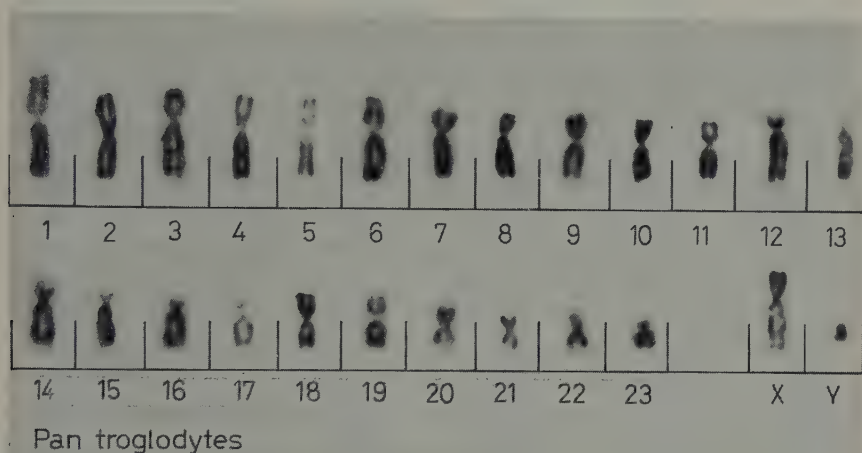


Fig. 4. Selected haploid set of the chromosomes of *Pan troglodytes*.

#### COMPARISON OF THE CARYOTYPE OF THE CHIMPANZEE WITH THOSE OF THE OTHER ANTHROPOID APES (GORILLA AND ORANGUTAN)

Gorilla and orangutan have the same number of chromosomes as the chimpanzee ( $2n = 48$ ). The other Old World primates have a higher or a lower number [CHIARELLI, 1968b]. Owing to the difference in number but mainly due to the morphological diversity of the caryotype we refuse to include the gibbons among the anthropoid apes [CHIARELLI, 1963].

They have had a completely different phylogenetic history and in many ways are more strictly related to the *Cercopithecoidae* than to the true anthropoid apes. Among the true anthropoid apes the caryotype of the chimpanzee is strictly similar to the caryotype of the gorilla.

The caryotype of the orangutan (fig. 5) presents several (at least 13) chromosomes which, from a morphological point of view, have nothing to do with the chromosomes of the chimpanzee.



The karyotype of the gorilla (fig. 6) instead appears strictly similar to that of the chimpanzee. This similarity appears particularly evident if we compare the single chromosomes of plates with the same total length that is to say with the same degree of spiralization. In this way each chromosome of chimpanzee is directly comparable with those of gorilla. The results of such a comparison is shown in figure 7 where individual homologues from the chimpanzee and gorilla are compared.

Chromosomes are divided into groups to make identification easier. In the first group containing 5 large sized metacentric and submetacentric chromosomes, a definite difference is seen to occur in the 3rd chromosome which in the gorilla is more submetacentric. In the second group consisting of 6 metacentric and submetacentric chromosomes smaller than the preceding ones, an actual difference was found in the 7th chromosome which in the chimpanzee shows a centromere in a more submetacentric position. The third group of 6 acrocentric chromosomes shows no conspicuous differences.

The same morphological identity pertains to the chromosomes in the fourth group consisting of 4 metacentric and submetacentric chromosomes and to those in the fifth group which contains two acrocentric chromosomes.

On the whole, the sex chromosomes seem to be very similar to one another also the X of the gorilla appears to be a little bit larger. The chromosomes which in the two African Antropomorphs appear to be different are thus pairs No.3 and No.7.

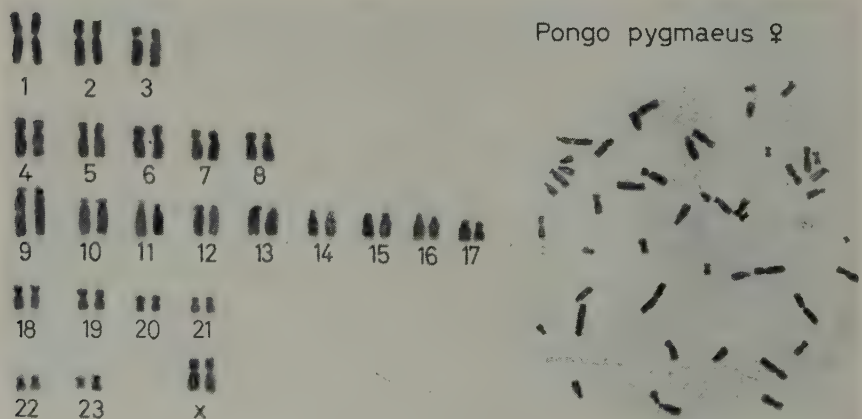


Fig. 5. Metaphase plate and reconstruction in pairs of the chromosomes of a female *Pongo pygmaeus*.



Fig.6. Reconstruction in pair of the chromosomes of a male *Gorilla gorilla*.

#### COMPARISON OF THE CARYOTYPE OF THE CHIMPANZEE WITH THAT OF MAN

Among the apes the caryotype of the chimpanzee is most similar to the human one. We can even state that, at first sight, it is difficult to distinguish at a morphological level the caryotype of chimpanzee from that of man. Using

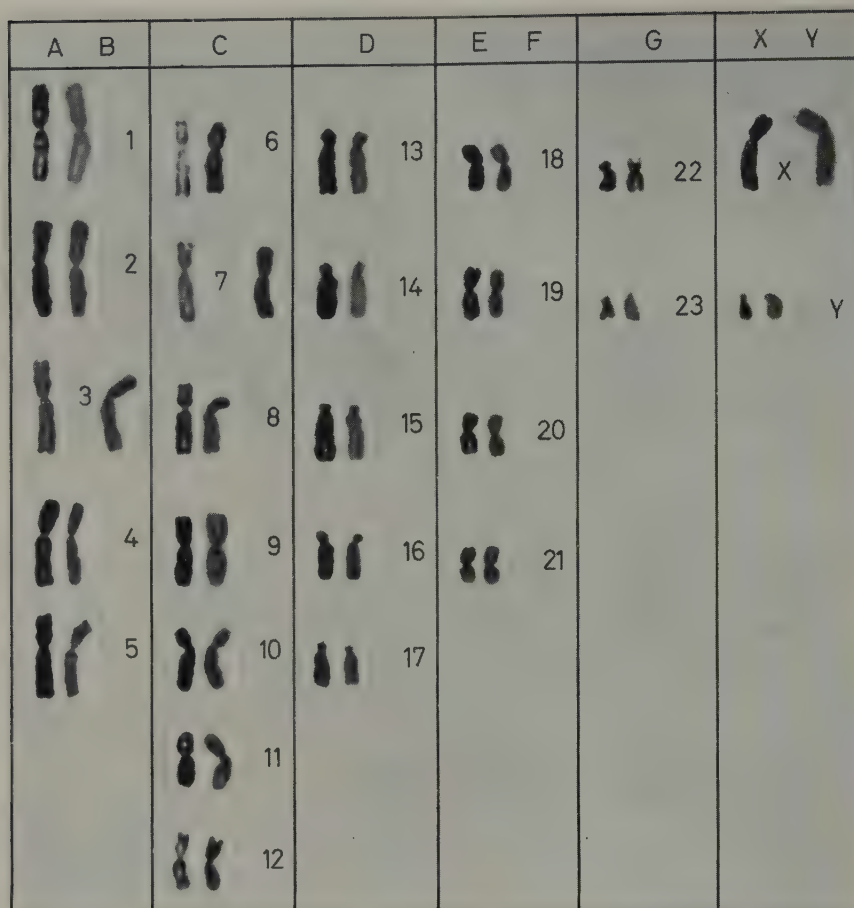


Fig. 7. Direct comparison of the single chromosomes of chimpanzee (on the left) and of gorilla (on the right).

the criteria proposed from the human karyotype [Denver Study Group, 1960; London Conference, 1963] the chromosomes of the apes can be divided into groups (table II).

The composition of these groups immediately shows a greater likeness between the karyotype of the chimpanzee and man. If we carry through a comparison between these two karyotypes according to their relative length and indices, or even better if we compare metaphasic plates of the same spiralization degree, (which we have in course but not yet completed), we may

get some idea of the actual morphological differences between the caryotypes of our species and the chimpanzee. The chromosomes which, by this method, we could at the moment demonstrate to be similar are reported in table III. With a certain approximation we can believe that during evolution these chromosomes did not undergo structural variations detectable at a microscopic examination, while the other chromosomes might have suffered more remarkable changes.

*Table II.* Tentative grouping of the chromosomes of the apes according the Denver and London classification for the human chromosomes

	Homo	Pan	Gorilla	Pongo
(A)	3	3	3+X	2
(B)	2	2+X	2	1
(C)	6+X	6	6	5+X
(D)	3	6	6	9
(E)	3	2	3	3
(F)	2	2	2	2
(G)	2	2	1	1

*Table III.* Morphological similarity of the somatic chromosomes among the chimpanzee and man

	3	6	7	9	13	16	19	21	22
Homo									
Pan	2	5	6	8	14	19	21	22	23

But the most obvious differences between the human karyotype and that of anthropoid apes is the number of chromosomes. Man has 23 pairs, while apes have 24. The most likely explanation we can advance for this difference in chromosome number is the hypothesis of a centric fusion between two acrocentric chromosomes which could probably have occurred in an 'ancestral Pre-hominidae' [CHIARELLI, 1961, 1962, 1968].

Naturally we may expect further and more detailed information when we could compare the behaviour of meiotic chromosomes of chimpanzee with the data on the meiotic chromosomes already known for man.



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Author's address: Dr. BRUNETTO CHIARELLI, Centre of Primatology, Institute of Anthropology, University of Turin, Turin (Italy).

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## CHIMPANZEE SOCIAL BEHAVIOR

W. A. MASON

Tulane University, Delta Regional Primate Research Center, Covington, LA

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### INTRODUCTION

Few problems in animal behavior are more deserving of careful investigation, or more difficult to study well, than chimpanzee social behavior. KÖHLER seemed to have both the potential rewards and the difficulties in mind when he said that a chimpanzee kept in solitude is not a real chimpanzee at all [KÖHLER, 1925]. He was alluding in this remark to two rather different ideas: First, the chimpanzee is strongly attracted to group living. It seeks the company of others and upon being separated from familiar companions, makes every effort to rejoin them. If it cannot do so, it becomes extremely agitated and distressed. During a prolonged separation, this state may give way to sullenness and depression, which quickly dissipate when the animal is permitted to rejoin its group. Secondly, many essential forms of chimpan-

zee behavior require the presence of other animals. In its social relations the chimpanzee reveals most fully those qualities of psychological complexity and subtlety that we have come to expect from an animal so close to man. Alone, the chimpanzee is cut off from that part of the environment which provides the incentive and the support that permit it to show the highest reaches of its abilities. All the conventional psychological processes—learning, perception, intelligence—are called into play in the service of social ends.

Because social behavior is the result of so many different factors, explanations always involve some speculation and one is constantly faced with the risk of assuming too little or too much. On the one hand, by rejecting all but the most parsimonious interpretations in an effort to avoid reading into the behavior of the chimpanzee the awareness, motivations, attitudes, and cognitive processes that we find in ourselves, we are likely to credit him with less than he deserves. On the other hand, it is all too easy to be taken in by resemblances that are superficial and to claim homologies where they do not exist. The wisest approach to chimpanzee social behavior, it seems, is to adopt the attitude that almost anything is possible, and to regard no interpretation as beyond suspicion until it is supported by rigorous proof.

Naturally, I will try in this chapter to avoid assuming either too little or too much, but at this stage in our knowledge there is small chance of complete success. My strategy will be a simple one: To accept the firmly established finding over the occasional anecdote, but where thorough documentation is lacking, to take the best evidence available.

My aim is to provide an overview of the chimpanzee as a social animal. We will begin with the mother and infant, move from there to a discussion of the structure of social groups, then turn to the different factors that contribute to orderly social relations. The first of these will be historical: those influences of constitution and experience that appear early and work cumulatively throughout life. The effects of regular variations in seasons and internal cycles will be considered next. Finally, under communication, we will take up the problem of social signals as factors in coordination, cooperation and social control.

#### MOTHER-INFANT RELATIONS AND THE DEVELOPMENT OF SOCIAL BEHAVIOR

The chimpanzee is born following a gestation period of about 8.5 lunar months. Like all simian primates it is equipped to cling to the mother, to

locate the nipple, and to suck. These responses do not appear to be as vigorous or as fully developed in the chimpanzee as they are in most other nonhuman primates and consequently the nursery-housed infant requires more diligent early postnatal care than the newborn macaque. Sucking is often sluggish during the first days of life, and when it appears the response is variable and spasmodic. The same is true of clinging, not only in the nursery, but apparently in nature as well, for as GOODALL notes, the wild-born infant requires almost continuous assistance and support from the mother during the first few days of life [VAN LAWICK-GOODALL, 1967]. If the mother is inept or fails to handle the infant properly, its chances of survival are slim.

Clinging and sucking are two of the primary means of maintaining contact with the mother. A third means is provided by vocalization. The infant chimpanzee is ordinarily silent unless it is distressed, whereupon it whimpers or screams. The effect of these sounds on the mother is typically galvanic, but the specific response she makes varies with circumstances. If the infant is losing its grip on her, for example, she pulls it close; if it is crying in response to the unwanted attentions of another animal, she may scoop it up or threaten the intruder off. Under any circumstances the net effect of her actions is usually to enhance or re-establish contact with the infant. For its part, nothing seems to calm the infant more quickly or to yield a greater sense of security than being properly held – in a position of ventral contact with the mother, with its hands engaged in her fur. So situated, the infant seems insulated from the outside world and buffered against disturbing experience. We have found that while it is being held the infant is less likely to vocalize in response to a painful stimulus, and its heart rate is lower than it is when there is no chance to cling [MASON and BERKSON, 1962; MASON and CANDLAND, unpublished].

These observations serve to emphasize the ecological and homeostatic elements in the infant's early adjustment to the mother: Ecological, since from the newborn infant's point of view the mother is less a social being than a niche or place to which it is prepared at birth to adapt; homeostatic, because the infant is able through the few responses available to it to bring about changes in the behavior of the mother that relieve tension or distress and contribute to its comfort and well-being. We must be careful of pushing this view too far, however, for development is a steady growth toward independence, and with each movement forward the ecological and homeostatic elements in the infant's relation to the mother become less pronounced.

The first indications that the infant is responding to the mother as though she were something more than a snug nest and a source of food, come



within the first three months of life. It begins to crawl about on her body, to peer into her eyes, to poke and pry into her physiognomy, and to treat her in many respects as an interesting piece of furniture in the world it is beginning actively to explore [VAN LAWICK-GOODALL, 1967; YERKES and TOMILIN, 1935]. We know from FANTZ's [1965] investigations of the early perceptual development of chimpanzees and human infants that visual preferences are shifting towards more complex patterns and outlines during this time, and it is likely that comparable changes are occurring in other modalities as well. Gradually the infant is putting together the information it acquires through sight and taste and touch and smell to form an integrated perception of the mother as an 'object' – a complex entity that moves through space, and that maintains a certain constancy of attributes and functions despite radical transformations in spatial orientation, contour and the juxtaposition of parts. It is embarked, in short, on developing its first relation with another social being.

The mother contributes to this development in myriad ways. Most simply, she does so by continuing to perform those activities that she must perform to guarantee her own survival and, incidentally, the survival of her infant. As she goes about her daily round – foraging, feeding, climbing, running, walking, interacting with other animals – she exposes the infant to varied patterns of stimulation and she creates new requirements to which it must adjust. Her status as a separate social entity is further developed by acts directed specifically toward the infant; she grooms it, restrains it, changes its position, and embraces it more closely. Maternal coercion and constraint will naturally increase with changes in the tempo and range of infantile activities. The mother comes more and more to assert herself as an individual whose interests are sometimes at variance with those of her child. Chimpanzee mothers are notably indulgent, but inevitably the day arrives when both will want the same tasty morsel of food, when one wants to be held and the other doesn't want to hold, when one wants to play and the other wants to sleep. If it comes to a physical contest, the mother would naturally win, but the issue is seldom resolved so simply. The indications are clear that the mother often gives in to the cries, the begging gestures, the tantrums and other importunings of her infant [VAN LAWICK-GOODALL, 1967; TOMILIN and YERKES, 1935]. Surely, these episodes provide some of the first lessons that give-and-take is the very essence of social intercourse.

The mother also contributes to the development of her infant by serving as a teacher and a model. Although there is no need to assume that she is guided by an explicit pedagogical plan, it is clear that her behavior has the

effect of encouraging the infant in certain activities and deterring it from others. YERKES [1943] was probably the first to call attention to the occurrence of maternal tuition in the chimpanzee, although others have since confirmed the behavior. YERKES' observations suggested that the mother aids and encourages locomotion, at first by holding the infant aloft by an arm or a leg or placing it where it can cling and climb; later by putting it on the floor and seemingly soliciting it to come to her.

Perhaps the combination of idleness and relief from the ordinary burdens of maternal care that exists in captivity is conducive to this form of maternal tuition; in the wild the mother probably serves less as a teacher than as a model. She is repeatedly demonstrating by her example which objects are sought and which are avoided, what is eaten and what is not, and how to build nests, open coconuts, fish for termites, or extract water from a hole in a tree. The infant watches closely while such acts are performed. How much information it actually derives in nature from maternal example is not known, but in view of the impressive potential for observational learning demonstrated in home-reared chimpanzees [e.g., HAYES and HAYES, 1952], the benefits are probably substantial.

By the end of the first year, the infant is able to locomote independently, and, although it is still under close maternal supervision, it has frequent contact with other adults, older infants, juveniles and adolescents. Wrestling and other play activities become more vigorous, and are directed increasingly toward other young animals. By the third or fourth year, the growing chimpanzee is no longer dependent on the mother for food or transport; it finds much of its own food and makes its own nest at night. It continues to associate with the mother closely, however, and travels with her most of the time until well into its fifth year. The occasions when mother and offspring are seen together diminish with the onset of puberty, although some ties may persist into full maturity [GOODALL, 1965; VAN LAWICK-GOODALL, 1967].

One would suspect that the varied experiences of the chimpanzee growing up in a natural group play an essential part in preparing it to function as an adult. This is certainly true, but only recently have deprivation experiments given us some understanding of the specific functions that are dependent upon experience [MASON, DAVENPORT and MENZEL, 1968; DAVENPORT and ROGERS, this volume].

It will be appropriate in closing this section on mother-infant relations and early social development to touch briefly on the question of individual differences in maternal behavior. As all students of chimpanzee behavior

have discovered, no two chimpanzees are alike. The same is true to a degree, of course, for any kind of animal, but in the chimpanzee, individual variability seems much more prominent than in other species, including most other nonhuman primates. It is clear, therefore, that any generalized description of maternal behavior can only be approximate in the individual case.

Variations in maternal care run from the extremes of oversolicitude and an excess of zeal, to comparative indifference and neglect. Most mothers, of course, fall somewhere in between and are neither generally good, nor generally bad, but perform adequately in some respects and poorly in others. Thus, among the five females observed by YERKES and TOMILIN [1935], the primipara, Wendy, groomed her first born so assiduously as to denude it of hair over large areas of its body and she picked at bumps and abrasions until sores developed; yet, in other respects her maternal activities were not remarkable. By way of contrast, Mona, a multipara and the mother of twins, groomed her offspring infrequently, and even then her attentions were casual and perfunctory; yet, of the five mothers, she alone rocked or tried to comfort her young when they were fretful [YERKES and TOMILIN, 1935]. Variations in maternal solicitude and skill are by no means unknown in the wild. Melissa, one of the mothers observed by GOODALL, for example, failed to detach the placenta and allowed it to trail along the ground as she walked. Once it caught in some twigs and nearly jerked the infant from her grasp.

Outright failures of maternal care are more frequent in laboratory or zoo populations than in the field. One advantage that the primiparous wild-reared chimpanzee enjoys over most animals born in captivity, of course, is a lengthy exposure to infants and mothers. She has not only her own experience in being 'mothered' to draw upon, but in addition has had the opportunity to observe mothers caring for their infants and to play at mother with her younger siblings. Anyone who has seen the VAN LAWICK's film of young Fifi interacting with her infant brother Flint, will find it hard not to conclude that Fifi's own offspring will derive some benefit from her experience.

That such experience does, in fact, make an important contribution to maternal adequacy is suggested by many observations on the behavior of captive chimpanzees with their first born. The observations of YERKES and ELDER can be taken as representative: '... the inexperienced individual, when her first infant appears, may act as if bewildered, frightened, incredulous or mystified, and completely at a loss what to do. After some hesitation and delay, with sensory examination of the stranger, she may either take it up and care for it with a measure of appropriateness, or instead treat it as an

object of curiosity, to be examined and tested in many ways, pushed or turned about, poked, sniffed at, even gently bitten, but not permitted to grasp and cling to her, much less to be hugged and carried about' [YERKES and ELDER, 1936, pp. 282-283]. Later, NISSEN and YERKES [1943] added the significant observation that completely inadequate infant care in their sample of 49 cases occurred only with the first born, implying that apart from pre-maternal factors, the experience of motherhood itself, can improve maternal adequacy.

#### GROUPING BEHAVIOR

Unlike many primates, including the other great apes, the chimpanzee shows little if any tendency toward a single, stereotyped, grouping pattern. NISSEN, from the evidence available in 1946, concluded that chimpanzees live in family groups comprising a large adult male, several adult females, and children ranging from infants to young adults. He placed the group size at between 4 and 14 [NISSEN, 1946]. More recent findings are consistent with NISSEN's conclusion that chimpanzees are often found in small groups, but they indicate that composition does not always conform to the pattern he described [GOODALL, 1965; ITANI and SUZUKI, 1967; KORTLANDT, 1962; REYNOLDS and REYNOLDS, 1965]. Both size and composition can be influenced by a number of factors, one of the most important of which, according to the REYNOLDS, is the availability and distribution of food sources. In the Budongo forest in Uganda, where their observations were made, as many as 15 animals could be seen in a single tree or in a patch of neighboring trees during fruiting seasons, whereas at other times bands of three or four animals were the rule. The composition of these bands was variable, although certain types occurred with greater frequency than others: (1) *Adult bands*, containing mature animals of both sexes and occasional adolescents, but not including mothers with dependent young. (2) *Adult male bands*. (3) *Bands of mothers with young*. (4) *Mixed bands*, containing adults and young of both sexes. GOODALL also notes the apparent absence of stable groups in her Gombe Stream population in Tanzania and the greater frequency of certain grouping patterns. Of a total of 350 temporary groupings observed, mixed groups accounted for 30%; all male groups or males on their own, for 28%; and females with young, for 24%.

The picture that is emerging from these recent field observations suggests that a more or less stable population of perhaps 40 or more chimpanzees occupies a given area. This region may be as small as 6 to 8 square miles for



forest-dwelling animals, according to REYNOLDS' [1965] estimate, and is probably much larger for those living in more open habitat [ITANI and SUZUKI, 1967]. The members of this population are familiar with each other and can be regarded as forming a single loosely organized community [ITANI and SUZUKI, 1967; REYNOLDS, 1965; VAN LAWICK-GOODALL, 1968]. Animals meet frequently; they may move together for a few hours or a few days, then drift apart, only to meet again at some future date. When individuals or small groups come together after having been apart for some time, there is a striking increase in calling, branch-waving displays, and other evidences of intense excitement, but after these preliminaries have been completed, groups merge and ordinary activities are resumed [GOODALL, 1965; REYNOLDS and REYNOLDS, 1965].

#### SOURCES OF ORDER IN SOCIAL BEHAVIOR

##### *Historical Factors*

The sources of order in such a natural community are not fully understood, but it is clear that they are many and that they operate on different levels. In nature, one of the most important levels is probably historical. The prolonged period of social dependence would seem to create an ideal opportunity for the growing chimpanzee to establish close acquaintance with the animals that fall within the mother's circle. Among these, of course, are older siblings – who may continue to associate with the mother and with each other into early maturity and perhaps beyond – as well as the youngsters of other females who are met in the company of their own mothers.

##### *Preference and Aversions*

Such contacts can be presumed to lead to the friendships and the antagonisms that have been observed in the field and in captivity. Thus, YERKES [1943] described two adult females, Dita and Fifi, long acquainted but usually living apart, who fought until one had finally gained the upper hand whenever they were caged together. At the opposite extreme were Josie and Wendy, also adult females, who groomed together, played together, shared food with each other, defended each other, and became restless and apparently unhappy when it was necessary to keep them apart [NISSEN], 1951. Little is

known about the factors that cause two animals to become determined antagonists or the best of friends. It is possible that both phenomena require the confinement and intensive exposure of laboratory living to develop fully. Such evidence as we have suggests that when a small group is housed together for a period, each animal develops a hierarchy of preferences for the others in the group. In one experiment, each of five young chimpanzees (two normal males, one castrate and two females) was given the opportunity to select a companion from among the other members of the group [NOWLIS, 1941]. Although each animal showed consistent preference, there was no indication that some animals were generally more popular than others, with the possible exception of the castrate male which no one seemed to prefer. Apparently, the major determinant of preference was compatibility of activity patterns. The animal disposed toward social play tended to select a partner that was also playful, whereas the animal that preferred grooming behavior selected a companion that was similarly disposed.

Although compatibility of activity patterns is probably an important factor in the development of a preference for a particular companion, and may even be required for its continuation, it would be shortsighted to conclude that nothing further is involved in chimpanzee friendships. It is safe to assume that the longer the acquaintance between two compatible animals, the more subtle and diversified their relationship becomes. Each animal grows more proficient in 'reading' the behavior of the other, in anticipating its actions, and in adjusting its own responses to the requirements of the social situation. Sharing food, grooming in response to solicitation (even to the point of directing attention to a particular spot indicated by the soliciting animal), and lending support during fights are common examples of such adjustments and seem to be but a step removed from the episode reported by MILES [1963] in which an adult male carefully removed a foreign particle from the eye of his mate after she had solicited his help.

But if it can be said that chimpanzees form lasting friendships, it is no less true that they are capable of abiding antipathies and aversions [NISSEN, 1951]. The frequency of chronic dislikes and the conditions under which they develop cannot be determined from present information. YERKES [1943] took the position that the mature chimpanzee possessed '... a persistent drive for social status ...', which gave rise to contests for social supremacy, sometimes of long duration. Perhaps such contests do occur, but they are not a prominent and inevitable element in chimpanzee social life. A drive for social status is questionable and if it exists, it probably plays no significant role in the development of interpersonal antipathies and aversions. Fighting is

seldom frequent or prolonged, and is probably more often a symptom than a cause of chronic incompatibility. Even animals that are on the best of terms will fight briefly on occasion, after which cordial relations are resumed. Most probably, interpersonal dislikes are based on the same factors that determine mutual attraction: Each animal brings into the social situation a unique constellation of traits – those qualities of temperament, activity preferences, and dispositions to behave in specific ways – that comprise his ‘personality’. The degree to which two such individual constellations mesh or clash is the major determinant of compatibility.

### Temperament and Enduring Individual Traits

To the reader sensitive to current attitudes toward loose talk in descriptions of animal behavior, reference to ‘friendship’ and ‘personality’ among chimpanzees is bound to raise the specter of anthropomorphism. Admittedly, there is some cause for concern – after all such terms are vague, and they usually *are* reserved for man. But there is also some justification for applying them to chimpanzees, though it is hardly sufficient to satisfy the determined critic.

Everyone who has worked closely with these animals has at times found it natural and necessary to use such words as ‘timid’, ‘moody’, ‘sneaky’ and ‘friendly’ to describe individual animals, and anthropomorphic or not, there are no other names that serve as well. As HEBB has put it, exposure to a group of adult chimpanzees gives one the overwhelming conviction that one is dealing with an essentially human set of attitudes and motivations [HEBB and THOMPSON, 1954]. Most experienced observers are convinced that chimpanzees display stable traits, tendencies, moods and the like, and in formal tests such persons have shown remarkably good agreement in their ratings of specific animals. CRAWFORD [1938] asked five judges to rate nine young chimpanzees on 16 traits such as friendliness, timidity, stability and excitability. The reliability coefficients were all over 0.70 and averaged 0.86 [NISSEN, 1956].

It should be noted, however, that these findings establish only that there is some consensual support for intuitive judgments of chimpanzee personality characteristics. They do not establish the objective bases for such judgments. The information that we use in describing chimpanzee personality was of the particular concern to D.O. HEBB, who addressed a series of papers to this question [e.g., HEBB, 1945; 1946a; 1946b; 1949]. The essential finding to

emerge out of this work is that intuitive judgments are based not only on the nature or frequency of discrete acts, but more often on the temporal relations between different acts. It is characteristic of our intuitive approach to human personality, of course, to operate within a broad time span. We believe that the significance of a smile depends less on the number of teeth that are showing than on the behaviors that precede it and follow it. HEBB makes a convincing argument that we follow the same approach when we deal with chimpanzee personality traits.

HEBB's groundbreaking efforts have taken us a step closer to putting the study of chimpanzee individuality on a scientific footing. We have a clearer idea of how we arrive at our intuitive judgments, and a stronger conviction that such judgments are not entirely subjective and capricious. The most important questions, however, are still unexplored. We are far from understanding the sources or structure of chimpanzee personality. The stability and generality of individual attitudes and traits and their role in social adjustment are, for the moment at least, largely beyond our ken.

### Dominance and Social Status

In spite of the lack of detailed information on individual traits, however, we can safely assume that chimpanzees will differ from each other reliably, not only in size and strength, but also in excitability, aggressiveness, the volume and vigor of their displays, as well as many other attributes that serve to intimidate others. (Anyone who has been charged by an adult male, an adult female and a juvenile, caged or otherwise, will surely agree that differences in the ability to intimidate are real.) The view taken here is that 'dominance' and 'subordination' are simply conventional designations for the fact that chimpanzees often stand in the relationship to each other of intimidator and intimidated. Naturally, we would expect the larger, stronger, more boisterous, and more aggressive animals in any group (being intimidating to almost everyone else) to display a kind of generalized dominance status. Presumably this accounts for the fact that in the wild, mature males are generally dominant over adult females, and they, in turn, are dominant over adolescents and juveniles [GOODALL, 1965; see also HEBB, 1946a]. Apart from this observation, however, there is no indication that chimpanzee groups as a whole are organized hierarchically; nor is there any convincing evidence of an autonomous drive for social supremacy. Chimpanzees are willful, impulsive, and greedy, certainly a sufficient basis for the development



of dominance and subordination, without the participation of specialized social motives and needs.

Dominance and subordination can thus be regarded as the natural by-products of social intercourse, and but one facet of the relationship between two individuals. In natural communities it seems likely that the status of each adult animal is fairly well-defined in relation to every other individual: '... it was often possible to predict when for example two chimpanzees met on a narrow branch, which animal would gain right of way' [VAN LAWICK-GOODALL, 1968; see also REYNOLDS, 1965]. It is not true, however, as the foregoing quotation seems to imply, that the subordinate's only response to the dominant animal is withdrawal. It seems likely, in fact, that large and stable differences in dominance may exist together with strong attraction. This is certainly the case for the rather special relationship between mother and young, but one would expect to find it as well within the relatively stable small bands of males that GOODALL, REYNOLDS, and others have observed.

The experimental data are consistent with the view that mutual attractions may develop between animals that differ reliably in social status. In immature chimpanzees, at least, dominance and social attraction are largely independent of each other. NOWLIS, during his investigation of companionship preferences, also tested dominance, using both competition for food and for escape from noxious stimulation as his measures. Dominance was clear, but was unrelated to social preference; animals preferred companions that were dominant over them as often as those that were subordinate [NOWLIS, 1941].

To consider dominance-subordination strictly in terms of the operational definition of success in a competitive situation, however, is to take an overly narrow view of social status. If one animal is intimidated in some degree by another, its status should be reflected in most of the interactions between them. Some indication of the range of behaviors that are associated with subordination is provided by field observations [VAN LAWICK-GOODALL, 1967, 1968]. Included are not only the common primate responses of withdrawal, presenting, grimacing, crouching and vocalization (screaming, whimpering, squeaking), but a number of behaviors that are seldom seen in other nonhuman primates, such as extending the open hand, bobbing, bowing, kissing and embracing. Observations on captive chimpanzees suggest that apart from these rather dramatic indications of status, animals tend to direct much more grooming behaviour toward a dominant partner than toward a subordinate. This has been reported not only for immature individuals, but for adult females as well [CRAWFORD, 1942a; 1942b; NOWLIS, 1941]. In one experiment, for example, 54 pairs of females were observed

immediately after they were brought together following varying periods of separation. Grooming occurred in 42 pairs, and in 76% of these cases the behavior was initiated by the dominant animal (dominance determined by subsequent competitive tests). Furthermore, only the dominant animal was observed to solicit grooming by holding out an arm or foot [CRAWFORD, 1942b].

Whether we are fully justified in speaking of leadership as a separate attribute of status in chimpanzees is problematic. Since groups lack a stable membership, it is difficult to isolate specific functions – such as defending against predators, heading group travel, or breaking up fights – that are performed consistently by one individual. Nonetheless, it does seem clear that some individuals exert a special influence over others that cannot be simply explained in terms of either their ability to intimidate or to attract them. Perhaps, both attraction and intimidation are involved in some degree, as seems to be the case with highly dominant males in other primate societies [e.g., JAY, 1965; SCHALLER, 1965]. Whatever the explanation for the phenomenon, both GOODALL and REYNOLDS recognized that certain males often took the initiative and were followed by others. Thus, GOODALL writes: 'On many occasions when the leader leaves a feeding tree the others immediately climb down and follow. ... once, when leaving a feeding area, David turned his head toward three other males, gave a low 'huh' and the others at once got up and followed him' [GOODALL, 1965, p. 454].

### *Seasons and Cycles*

Imposed on the historical factors that form the stable core of chimpanzee social relations is the influence of natural cycles, originating in the environment and within the individual. These provide an additional source of regulation and control over social relations. Diurnal cycles of course have obvious effects. The chimpanzee is an early riser, up and doing soon after the sun has risen. The early morning is spent in active feeding and in traveling between food sources. A rest period, given over to grooming, napping, or just sitting quietly, occurs during the middle of the day; a second period of intensive feeding starts around 4:00 p.m. and continues until dusk, when the construction of sleeping nests begins.

Beyond the daily cycles are seasonal variations in temperature, in rainfall and in the availability and distribution of food and cover. These create a shifting pattern of forces to which the individual and the community as a

whole must accommodate themselves. Equally fundamental cycles are present within the individual and these, too, create pressures and predispositions that exert a regularizing influence on social relations.

Of these two broad classes of cyclic influences, those relating to the seasons are the most pervasive, the most complex, and the most difficult to analyze in causal terms. Nevertheless, field workers have been able to demonstrate that seasonal changes do indeed play a significant role in chimpanzee group behavior. REYNOLDS [1963; 1965; REYNOLDS and REYNOLDS, 1965] has gone furthest in exploring this question, especially the importance of food sources. In the Budongo Forest he observed three distinct food cycles: the fig season, the ngrube season (the ngrube is a small orange fruit, less preferred than figs), and the lean season. During the lean season, when food is scarce and scattered widely, chimpanzees are relatively silent; they range over several square miles a day and they usually travel in small bands. When rich supplies of food are concentrated in one area, the level of vocal activity increases sharply, mobility is reduced, groups are larger and more time is spent in grooming. The 'carnivals' of tree-drumming and shouting noted by REYNOLDS, NISSEN and others are especially prominent during this period and may go on for several hours at a stretch, presumably a reflection of a general increase in excitement and the overall level of social interaction.

In contrast to Budongo, the Gombe Stream Reserve has only two well-defined seasons, wet and dry. Shortly before the onset of the wet season, chimpanzees begin to spend much time moving about in large groups. Accompanying this change in group size, there is a noticeable increase in the tempo of social behavior. Male ground-slapping and branch-waving displays become more frequent, more chasing is observed among adults, the distances covered during a day may be greater, and there is an increase in vocal activity [GOODALL, 1965].

Although there is no indication that chimpanzees display a narrowly circumscribed breeding period, GOODALL's observations suggest that sexual behavior is also more frequent during this season. A moderate seasonal effect has also been detected among captive animals. Females in Orange Park, Florida, particularly the younger animals, tended to develop a temporary amenorrhea during the winter and the entire reproductive cycle was prolonged – from a mean length of 35 days for July, to 43 days for December [YOUNG and YERKES, 1943].

The female reproductive cycle also provides one of the clearest examples of an internal cycle with important influences on social behavior. There are probably others, but none so accessible to scientific observation or so tho-

roughly documented. In the mature female chimpanzee, the sex cycle averages about 36 days and is accompanied by a pronounced swelling and detumescence of the ano-genital area. As the genitalia swell, the female becomes more receptive, and also more attractive, to the male. In captivity, animals that are on congenial terms mate only during a few days in the cycle when sexual interest is at its peak; overtures may be made by either sex. In nature, where animals do not live in pairs, there is no evidence of a temporary and exclusive consort relationship in the manner described for many monkeys, nor is there any indication of hostility or competition among males. On the contrary, sexual relations seem remarkably casual and easy-going and several males may assemble around a receptive female, each copulating with her in turn [GOODALL, 1965; REYNOLDS, 1965].

Apart from her greater willingness to accept the male, the female exhibits behavioral changes of a more general nature during the receptive phase of her cycle. She becomes more irritable, bolder and more self-assertive. These changes are probably an integral part of the general adaptive pattern associated with estrus, since without some additional internal bolstering, most females might be thoroughly intimidated and flee from the close attentions of dominant males. Whatever its adaptive value, it is clear that a significant change in her comportment does occur, and that it affects her relations not only with males, but with other females. The clearest evidence is derived from competitive tests for food, admittedly an artificial situation, but one which taps one of the chimpanzee's most persistent interests and has the additional virtue of supplying a reliable quantitative measure. YERKES was probably the first to find that in many pairs in which the male retained exclusive control over the food chute most of the time, a complete reversal in food dominance occurred when the female was at the height of her swelling. Not all pairs conformed to this pattern, to be sure, but enough did to indicate that the phenomenon was real and of some generality [YERKES, 1940]. Subsequent research has shown that essentially the same shift in food dominance occurs even when both partners are females [CRAWFORD, 1940; NOWLIS, 1942]. Furthermore, female dominance can be raised experimentally by administration of estrogen, which induces genital tumescence, and androgen, which does not [BIRCH and CLARK, 1946]. YERKES suggested that reversal of dominance could be regarded as the 'granting of privilege' by the male – apparently in recognition of favors anticipated or received. But in view of the findings on reversals of dominance between pairs of females and the demonstration of hormonal control, it seems more likely that the important psychobiological changes are those occurring within the female herself.



*Communication*

Social behavior consists of two or more individuals doing something together. Courtship and mating, parental behavior, and the endless interplay between animals that characterizes daily life in a chimpanzee group, imply a high degree of coordination and reciprocity. How this is achieved is, broadly speaking, a question of communication.

Communication can be defined as the process by which information is transmitted from a social source to a social recipient. Despite this simple definition, however, the process is actually exceedingly subtle and complex: 'In animals, as in man, an act of communication is one of the most refined and intricate events in the behavioral repertoire. Initiated by one animal, which produces the communicatory signal, mediated by the environment through which the signal is transmitted, and culminating in the response evoked by the signal in the recipient, it spans both space and time' [MARLER, 1965].

Moreover, the effect of the signal will be influenced by the surroundings in which the signal occurs, the individual history and internal state of the recipient, and the nature of its previous relations with the animal transmitting the signal.

Chimpanzees are uncommonly adept at devising ways of communicating that are specifically suited to the circumstances in which they find themselves. Their communication displays a degree of 'openness' that is certainly uncommon, and probably unique among the nonhuman primates. In most primates, BASTIAN writes, '... signaling systems are closed; that is, there is a finite – and actually a rather small – number of basic types'. He adds '... there has been a specialization of visual signaling in the higher primates related to changes in their facial and limb anatomy ... (but) ... what has been achieved by such anatomical changes can properly be called an interstitial openness in which there is increased intergradation and intermodulation between the types of basic signals' [BASTIAN, 1965]. Whether or not the openness displayed by the chimpanzee is merely 'interstitial', it is clear that on some occasions both the form of the signal and the message it communicates may be novel to the receiver, and yet the message is understood and is responded to appropriately.

On my first visit to the old Yerkes Laboratories at Orange Park, I was walking on the grounds unaccompanied when I noticed an adult female crouching at the front of her cage with a pine straw in her mouth. She had pushed the straw through the wire and from the way she looked at me, it seemed evident that I was expected to do something about it, so I approached

and removed it. Immediately, she moved her head to a different place a few inches away, put her open lips against the wire, and again gave me 'that look', whereupon I returned the straw. She accepted it, changed her position slightly, once again offered it to me and I took it. And so we continued our little game of passing the pine straw back and forth, until eventually I tired of it and quit. When I mentioned the episode to HENRY NISSEN he immediately named the animal, and indicated it was a common pastime of hers. Although I was unfamiliar with the animal and indeed with chimpanzee behavior in general, I was recruited into a game that I did not know and was led to play it according to 'rules' that were established by another individual.

Later, when I was working at the Yerkes Laboratories, one of my first projects was to investigate communication in chimpanzees. The apparatus was identical to one that I had used successfully with rhesus monkeys [MASON, 1959], but the chimpanzees were doing very badly with it and some of the animals were becoming resistant to entering the work area. One of the more reluctant was Malcom, a laboratory-born male, about 4 or 5 years old at the time. Our practice was to carry the subjects to and from the work area and we indicated that we wanted the animal to come to us in the usual way, by extending both hands with the palms up. This is a bimanual version of the normal chimpanzee begging response, but it is also the signal used at times by the natural mother to get the young animal to climb on and it was in this way that Malcom usually responded to it. On this occasion, however, he steadfastly refused to come to me, and as I continued to urge and wheedle, he reached to the floor of his cage, picked up a well-formed stool, and laid it gently in my outstretched hand. Afterwards, I found it a simple matter to get him to exchange onions for grapes, or chimcrackers for bananas, simply by extending one hand and proffering the desired object in the other. In spite of my best efforts, however, I was unable to train Malcom to 'communicate' in the formal test apparatus in which the monkeys had performed so well.

Anecdotes could be multiplied. Anyone who has had close contact with chimpanzees will no doubt have his own favorites that reveal something special about chimpanzee communication that must be left out of conventional scientific accounts. But what useful purpose do such stories serve? Chiefly, I think, to remind us that when we direct our attention to chimpanzee communication we aim for a most elusive target. Nowhere is the individual variability referred to so often in this chapter more prominent; nowhere is the impression of a twilight creature more compelling; nowhere is the tight-rope that separates fact from romantic fancy more difficult to walk; and

nowhere is a statement about chimpanzees 'in general' more likely to leave the illuminating particular out of the account. And, to correct the impression that all these difficulties are a credit to the chimpanzee, it should be added, that nowhere is the great unevenness of its accomplishments more evident. Behaviors that (by human standards) seem perceptive to the highest degree can exist side by side in the same individual with behaviors that (by the same standards) suggest an opacity of monumental proportions.

Yet, when we turn to generalized descriptions of chimpanzees communication, neither the remarkable 'highs' nor the unexpected 'lows' are apparent. The basic behavioral elements that serve as signals in chimpanzee interactions are much the same as those described for many other primates [ANDREW, 1964]. Each individual has a sizeable inventory of sounds, postures, and facial expressions that comprise his potential repertoire of signals. The frightened or frustrated chimpanzee screams or whimpers, and there is a characteristic facial expression associated with each of these sounds. The sight of food, and the appearance of a favorite companion is accompanied by barks and grunts, or, if excitement is intense, by screaming. Threat is associated with glaring, compressed lips, piloerection, bipedal standing, stamping, and swaying from foot to foot, often as a branch or similar object is held in one hand and shaken or waved back and forth. Some of the same components seen in threat may also be directed by the male toward a female when she is in swelling, but he makes other responses that seem specific to the sexual situation, such as sitting stiffly while displaying the erect penis and 'beckoning' by raising one arm to head level and making a rapid sweeping movement toward himself [e.g., REYNOLDS and REYNOLDS, 1965; VAN LAWICK-GOODALL, 1968; WILSON and WILSON, 1968].

The list is not complete, but these examples are sufficient to indicate the kinds of responses that provide the raw materials for signaling behavior. The more obvious and dramatic signals are rather closely tied to the level of emotional arousal of the signaler. They give information primarily about his motivation, mood, or intent, and only indirectly, if at all, about events occurring in the external environment.

What is difficult to convey in a generalized account, is the chimpanzee's capacity for subtle variation. This is evident not only in the form of the signal – where the slightest of intention movements may come to convey a wealth of information – but most particularly, in the response to any given signal. This may be entirely covert, it may consist of nothing more than a glance or a slight change in spatial relations, or it may be more obvious than the signal itself.]

For the chimpanzee, the context in which the signal occurs plays a fundamental part in determining the nature of the response that will be evoked. All sources of information are taken into account. The response is influenced by the identity of the sender, the physical situation in which the signal occurs, and by the presence and location of other individuals. A scream from a friend may call forth aid, whereas the same cry from a stranger could easily provoke an attack.

HENRY NISSEN said that almost everyone who has worked with chimpanzees formed the impression that they were closer to us in their social intelligence than in their intelligence in conventional problem-solving situations [NISSEN, 1951]. This is also my impression, and I therefore find it puzzling that formal attempts to assess the chimpanzee's capacity to use 'social' information in solving problems have met with so little success. My own failure with Malcom has been mentioned (and performance was no better among the five other animals in the group). Against the entirely reasonable criticism that the deficiency was in the method and not the chimpanzees, one must weigh the positive results obtained with the same apparatus on monkeys and severely retarded, nonverbal, human children [MASON and HOLLIS, 1962; HOLLIS, 1966]. Furthermore, CRAWFORD and SPENCE had earlier tested the chimpanzee's ability to learn a simple discrimination by watching the performance of a trained demonstrator, again with indifferent success [CRAWFORD and SPENCE, 1939]. Also pertinent here are the difficulties CRAWFORD encountered in training chimpanzees to cooperate in pulling in a weighted box by means of an attached rope [CRAWFORD, 1937]. The animals were first trained individually to pull in the box to obtain food. When the weight of the box was increased so that coordinated pulling was required, each animal continued to pull without reference to the partner. To get the animals to pull together it was necessary for CRAWFORD to 'call strokes' by giving a verbal signal. As soon as coordinated effort was established in this way the animals learned to watch each other and the verbal signal could be omitted. But it is doubtful that without the initial help of the experimenter, the chimpanzees would ever have been able to achieve the degree of coordination required to solve the problem.

In contrast to the difficulties that were experienced in getting the animals to cooperate, however, subtle forms of communication emerged spontaneously once coordinated pulling was established. For example, CRAWFORD fed one of the animals to satiety before the test and, as expected, she was indifferent to the task. The partner, who was eager for the food, would urge and direct her to pull, and eventually she would comply, even though she had



no desire for the reward. Photographs of one of these sequences are presented in YERKES [1943]. To be properly appreciated, however, the behavior must be seen on moving picture film, and fortunately a published record is available.

The results of the foregoing research agree with KÖHLER's assessment: '... there is a sharp barrier to mutual comprehension, when one of these apes sees another executing intelligent new actions quite unusual among chimpanzees' [KÖHLER, 1925, p. 308]. The tasks we have considered, in spite of their apparent simplicity, probably all fall within this class. The catch, of course, is that two problems that seem to us to be equally demanding of 'intelligent new action' may yield quite different results.

At any rate, when behaviors are selected that are known to have some clear counterpart in the normal life of the chimpanzee, the outcome is more often satisfactory. Food-sharing is one such response, having been observed both in free-ranging and captive animals [e.g., KÖHLER, 1925; VAN LAWICK-GOODALL, 1968]. Typically, one chimpanzee solicits food from another by reaching out to touch the food or the lips of the possessor, or by extending his hand toward him with the palm up. The animal with the food may oblige by opening his mouth slightly, allowing the other to remove some food; he may push out a lump of half-chewed food and offer it; or he may detach a piece and place it in the beggar's hand (much as Malcom did to me).

This behavior will survive translation into an experimental setting, as NISSEN and CRAWFORD have shown, thus permitting a study of the variables that influence the tendency to share food and other desirable objects. They placed two animals in adjacent cages with a grille between them. One of the animals was supplied with food or with tokens that could be used in a vending machine to obtain food. They observed 266 instances of begging, more than half of which were successful. Animals responded more often to the begging of a friend than to an animal with whom they were not intimate, and they more readily shared tokens (which the beggar could exchange for food), than food. Since the possessor could not use the tokens himself, this result is not surprising, but it does indicate that the willingness to share is influenced by the value of the item to the possessor. Varying the hunger of either animal, however, had a negligible effect on sharing behavior [NISSEN and CRAWFORD, 1936].

The chimpanzee's strong natural interest in feeding activities must also account for YERKES' success in demonstrating suggestibility in young chimpanzees. While the animals watched, YERKES placed in his mouth a strip of filter paper – which is non-nutritious and seemingly tasteless to chimpanzee, as it is to man – and chewed it noisily and with evident satisfaction. By this

example, he was able to induce animals to accept and chew the paper, and on rare occasions, even swallow it [YERKES, 1934].

The achievements of home-reared animals seemingly are inconsistent with KÖHLER's observation that intelligent new actions cannot be easily acquired by watching another. It will be recalled that Viki was able to imitate correctly on command, actions that she had never before performed [HAYES and HAYES, 1952]. It should be noted, however, that this ability was acquired. Although Viki showed some spontaneous imitation during play, her real advances occurred only after formal training was instituted. At first it was necessary to reward her successful attempts with food or to put her through the actions of a new task many times before she began to perform it by herself.

The important point of the HAYES' experiment is that the full development of the ability to imitate required training, and the effects of this training were cumulative and progressive. Viki developed a social skill which she possessed initially in only rudimentary form. Once she had acquired a 'set' to imitate, she was able to copy entirely new acts (so long as the component responses were in her repertoire) by merely observing another individual perform.

One of the major lessons to be drawn from this chapter is epitomized by the HAYES' experiment. The peculiar challenge that the chimpanzee makes to the behavioral scientist is its potential for individual achievement. The 'average' chimpanzee, like the man on the street, is a convenient fiction. What impresses us most is not the lowest common denominator of performance – the normal social patterns that are shared by all chimpanzees – but the discrepancy between group norms and the few highly idiosyncratic achievements of the individual. The home-rearing studies remind us that given the right social setting, every chimpanzee has within it the potential of going far beyond what it could achieve under less favorable circumstances. Like man, the full development of its abilities requires the stimulus, the direction and the support, that can only be provided by other individuals.

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## OPERANT CONDITIONING RESEARCH WITH THE CHIMPANZEE<sup>1</sup>

FREDERICK H. ROHLES, JR.

Institute for Environmental Research, Kansas State University, Manhattan, KS

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### INTRODUCTION

In 1953, FERSTER published the first definitive paper on the methods and techniques of the operant conditioning experiment and centered his descriptions around the white carneau pigeon. Since then these techniques have been modified and expanded so that now the procedures of the operant conditioning experiment have been described for mice, turtles, fish, cats, dogs, as well as mentally defective and autistic children. Yet in most of these studies the detailed specifications of the techniques employed are, as FERSTER stated in the paper cited above, insufficient to permit 'duplication of the conditions of the experiment.' This is especially true of the operant

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conditioning research with the chimpanzees. Thus, the present paper will present the techniques of the free operant which have been developed for the chimpanzee by describing the specialized instrumentation which has been developed for this species and the types of behavioral repertoires which have been studied.

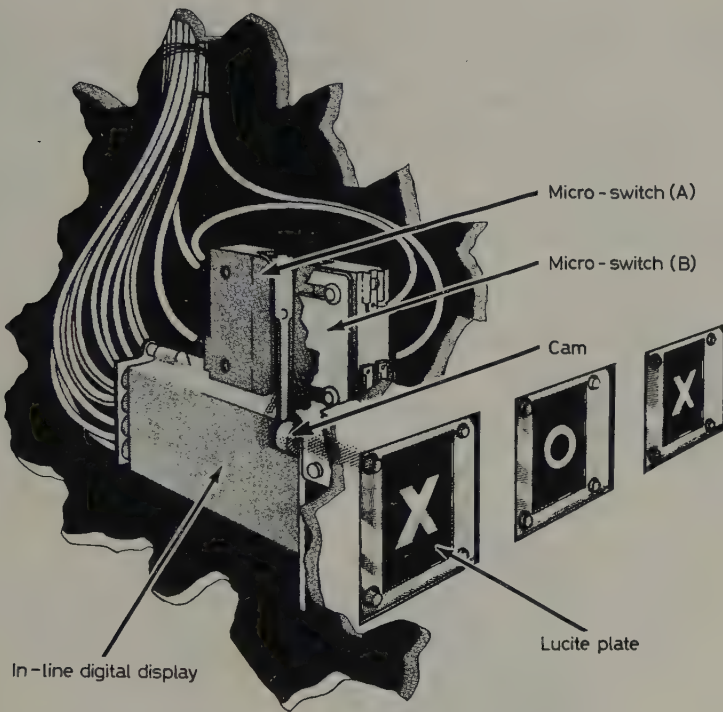
#### INSTRUMENTATION

To paraphrase FERSTER's 1953 paper, instrumentation of the operant conditioning experiment requires 1. an operandum, i.e., a device like a lever which the subject can manipulate and which operates a switch; 2. a recording system; 3. a reinforcement device to present and control the reinforcing stimulus; 4. a chamber or chair in which the animal can be placed and; 5. the control equipment to arrange the required contingencies between the operation of the operandum switch, reinforcement device, recorder, and any stimuli that might be presented [FERSTER, 1953, p. 264]. These are described for a variety of species by ROHLES [1969] and will be discussed below for the chimpanzee.

*Operandum.* The operandum for the chimpanzee usually takes one of two forms. The first is a lever much like a telegraph key, whose fulcrum and linkage to the switch are either outside the chamber or enclosed in a box when used with a chair. In most cases, the arm of the lever should be constructed of at least one-half inch steel or aluminum rod and while extreme care is given to the force required to activate the mouse, rat, and pigeon lever, little attention to this factor is required for the chimpanzee lever. The primary requirement is that it be rugged and that its excursion range from 0.50 to 0.75 in.

The second operandum developed for the chimpanzee by ROHLES and GRUNZKE [1961] is the Stimulus-Response Key (SRK). Available commercially, it incorporates a clear lucite plate and an In-Line-Digital Display, a single plane projection device capable of presenting one of 12 symbols or colored discs on a ground-glass surface. Pushing the plate activates the switch and mounting several SRK's side-by-side as shown in figure 1 permits study of 3 or 4 stimulus oddity problems or matching behavior.

*Recording system.* The main dependent variable in any operant conditioning experiment is response frequency. For the chimpanzee as for other species, this is recorded on a cumulative recorder, a device which provides a graph



*Fig. 1.* Stimulus-Response Key [ROHLES and GRUNZKE, 1961].

of the cumulative (total) responses as a function of time. Most recorders contain 2 pens which record 3 variables. The response pen 'is stepped across the paper a small distance for each response; at the same time the paper travels at a constant speed. The slope of the line that is drawn is directly proportional to the rate of the response. The virtue of the cumulative record is not that it allows a precise measurement of the rate at any particular time, but rather it emphasizes changes in rate which can be seen in the curvature of the record' [FERSTER, 1953, p. 267]. In addition to the actual lever presses, reinforcements are indicated by small momentary deflections of the response pen. The second pen serves as an event marker and is used to present a non-cumulative record of such information as errors or the presentation or withdrawal of a discriminatory signal.

A different approach to the measurement of response frequency is to determine the time that elapses between responses or the inter-response time (IRT). Devices to measure this variable are available commercially and their use results in the automatic construction of a frequency distribution of IRT's.



For brief experimental sessions simple digital counters are used for recording reinforcements, and correct, incorrect, and total responses, however if this information is required over a prolonged time period, a digital printer may be used. This device accrues information, lever presses, reinforcements, right and wrong discriminations – and prints the totals on a paper similar to an adding machine tape. By adding a timing device, this information can be totalled and printed for a specific time period with the counters being reset to zero for subsequent recording.

*Reinforcing devices.* The reinforcing device is an automatic piece of equipment for delivering the reinforcing stimulus to the animal. In the case of food reinforcement, dispensers are available for delivering a variety of sizes and flavors of pellets, however, the one-gram spherically-shaped whole-diet

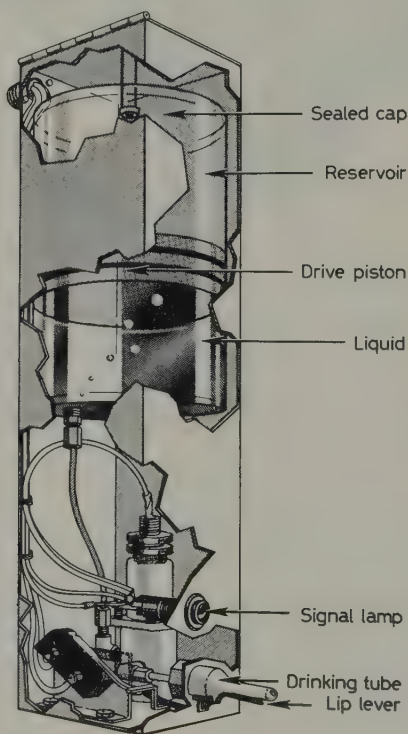


Fig. 2. Liquid dispenser for primates [GRUNZKE, 1961a]. Fig. 1, 2, and 6 appeared in W. HONIG (ed.) *Operant Behavior*, 1966 and are used with the permission of the author (F. H. ROHLES) and the publisher Appleton-Century-Crofts, Meredith Corporation.

banana flavored pellet is recommended. GRUNZKE [1961a] has developed and tested a water dispenser for chimpanzees. Shown in figure 2, it consists of a reservoir of water which can be drained through a solenoid-operated valve. When the animal bites the lip-lever drinking tube the valve opens momentarily and the water is delivered.

When the behavior is to be under the control of electric shock, a commercial shock generator with a 10 m.a. output is recommended. Electric shocks of this magnitude are usually administered to the soles of the animals feet while seated in a restraint chair. While heat and blasts of air have been used with lower animals, their effectiveness as reinforcing stimuli with chimpanzees has yet to be tested, however FALK [1958] reports using the availability of the experimenter's arm for the chimpanzee to groom as an effective reinforcer.

*Chamber.* The apparatus shown in figure 3 is the result of a three year effort to develop an operant conditioning chamber for a chimpanzee. It has a

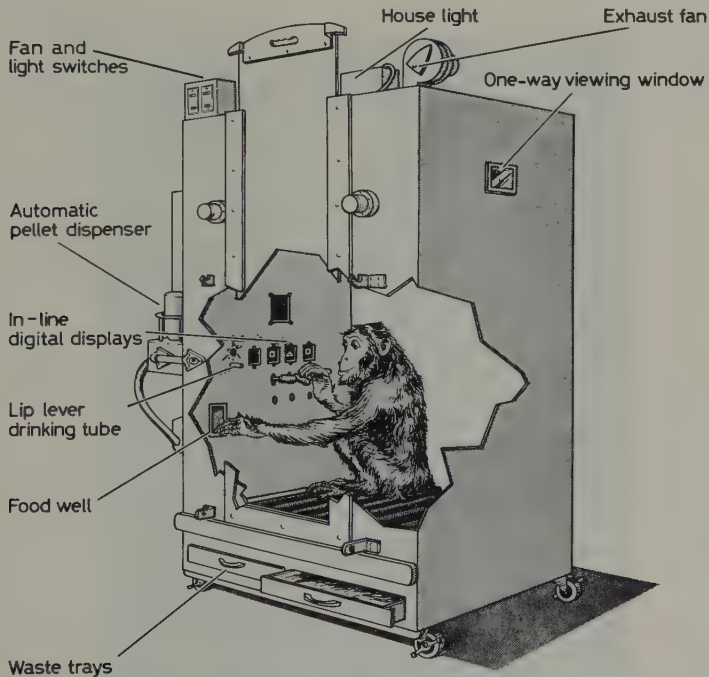
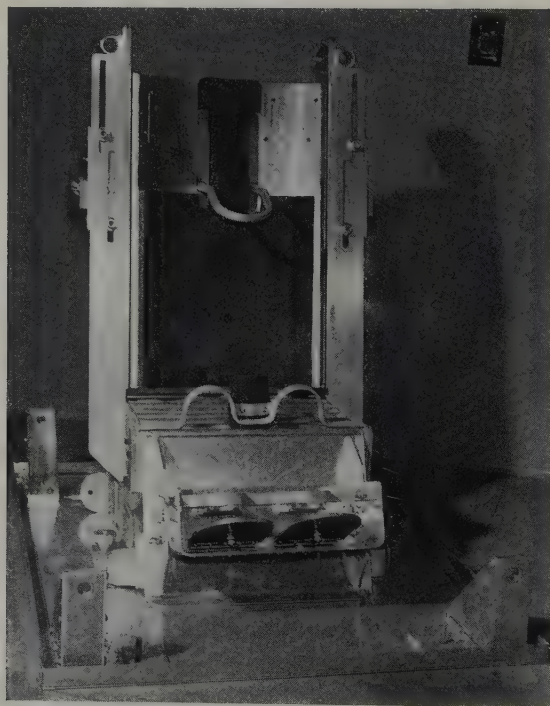


Fig.3. Operant conditioning chamber for a chimpanzee [ROHLES, 1961]. Fig.3, 5, and 8 were copyrighted in 1961 and are used with permission of the author and publisher, the Society for the Experimental Analysis of Behavior.

guillotine-type door which will accept a transfer or squeeze cage and its interior measures  $3 \times 3 \times 4$  ft. It has a GRUNZKE water dispenser (see above) with a lip-lever drinking tube and an automatic pellet dispenser which delivers reinforcement to the food well. Equipped with levers and stimulus-response keys, it has an exhaust fan, a houselight, and a one-way viewing port. It is constructed of 0.25 in. aluminum sheet, rests on heavy-duty, 3 in. locking casters, and the drop trays which are 8 inches below the floor, may be removed for easy cleaning.

Like the chamber, the restraint chair shown in figure 4 is the product of 3 years of testing in the Comparative Psychology Branch of Holloman Air Force Base, New Mexico Aeromedical Research Laboratory. Developed by M. E. GRUNZKE [1961b], it can accommodate chimpanzees weighing up to 80 pounds. In this chair, which is constructed of 0.25 in. aluminum, the animal is restrained by a neck yoke, an ankle yoke, and a yoke that fits across the thighs. Each of these is adjustable for different sized animals and the



*Fig. 4.* Chimpanzee restraint chair [GRUNZKE, 1961b].

*Table I.* Representative list of suppliers of operant conditioning equipment for chimpanzees

Supplier	O <sup>1</sup>	R <sup>1</sup>	C <sup>1</sup>	F <sup>1</sup>	P <sup>1</sup>	H <sup>1</sup>
BRS Foringer, 5451 Holland Dr. Beltsville Md. 20705	X	X	X	X	X	X
CIBA Pharmaceutical Co., Box 313 Summit, N.J. 07901					X	
Davis Scientific Instruments, 11116 Compton St. No. Hollywood, Calif. 91600			X	X		
Ralph Gerbrands, Co., 8 Beck Road Arlington, Mass. 02174	X	X		X		
Grason-Stadler Co. West Concord, Mass. 01781	X	X	X	X		
Lafayette Instrument Co., Box 1279 Lafayette, Ind. 47902	X		X	X		
Lehigh Valley Electronics, Box 125 Fogelsville, Pa. 18051	X	X	X	X		X
Massey-Dickinson Co., 9 Elm Street Saxonville, Mass. 01701			X			
P.J. Noyes, Co., Main Street Lancaster, New Hampshire 03584					X	
Research Equipment Co., Box 1151 Bryan, Tex. 77801						X
Schroer Mfg. Co., 2221 Campbell Kansas City, Mo. 64108						X
Scientific Prototype Mfg. Corp., 615 W. 131st New York, N.Y. 10027	X	X	X	X		

1 O—operanda; R—recording system; C—control equipment; F—feeders and reinforcement devices; P—food pellets; H—housing, chambers, and custom chairs.



entire chair is mounted on a litter which can be carried by two men. The chair is equipped with several speed-rail fittings to accommodate operanda and reinforcement devices.

The chair is particularly useful for shock avoidance reinforcement schedules because the shocks can be delivered to the animal's feet. This is accomplished by resting the subject's feet on broad brass plates which are equipped with springs so that no matter how the animal moves its feet, they are always in contact with the brass electrode foot-plate. As noted above, a shock of 10 m.a. is considered to be the appropriate magnitude for the chimpanzee.

In almost all cases, the chairs and sometimes the chambers are housed in sound-attenuated booths which serve to isolate the subjects from the routine noises and distractions of the laboratory, however, this is not as critical a requirement for chimpanzees as it is for other species.

*Control equipment.* The control equipment for the operant conditioning experiment with the chimpanzee is essentially the same as for other species. Both because the type of control equipment employed is dependent upon the type of behavior under study and because the details of the control equipment for operant conditioning research is described in other sources, ROHLES [1969], SIDOWSKI [1966], only a list of the commercial suppliers is presented. These are shown in table I and represent a partial list of the companies who manufacture the equipment needed for operant conditioning research with the chimpanzee. Several of these firms publish pamphlets containing the wiring schematics for the more simple reinforcement schedules and all provide free consulting service for any equipment or instrumentation problem; several conduct one or two day courses on the use of their equipment. In fact, it is no exaggeration whatsoever to state, that with the present-day logic-type equipment which is readily compatible with high-speed computers the instrumentation for the operant conditioning experiment is limited only by the imagination of the experimenter.

#### PRE-EXPERIMENTAL TECHNIQUES

The use of the chimpanzee in operant conditioning experiments as well as in other behavioral research presents several unique problems not relevant to other species. At the outset, because of the strength of even young animals, special caging facilities are required. Upon receipt of the animals it is a good procedure to isolate them not only from the rest of the colony which is the

customary practice, but also from a large number of trainers, assistants, and handlers as well. Strict and conscientious adherence to this quarantine with the minimum of human contact cannot be over-emphasized. During this period which usually lasts between 45 and 60 days, the animals should be weighed daily and tested for upper-respiratory infections as well as hepatitis and intestinal disorders arising from *salmonella*, *shigella*, and *strongellitis*. Dental examination should also be made. These activities are customarily performed by a veterinarian or pediatrician.

It is also during the quarantine period that taming and gentling procedures should be initiated. These can be done by the handler during feeding and while this part of the pre-experimental procedure is often omitted with other species, it is paramount to the ease of handling and training when the chimpanzee is the species of choice.

It was noted above that the one-gram banana flavored pellet manufactured by CIBA Pharmaceutical Company is excellent as a food reinforcement. Depending upon the size of the animal, between 125–200 of these will be used daily as rewards. As a general rule animals on a deprivation schedule when 'working' for most of their daily food should receive at least 850 calories per day and 250 cc of water. Purina monkey biscuits (10–11 calories each) may be used to supplement the pellet and 250 cc of a pabulum additive is suggested daily as a general dietary supplement<sup>2</sup>. In addition to this the animals should receive 5 cc of Incremin with Iron once a week (Incremin with Iron is the product of Lederle Laboratories Division, American Cyanamid Co., Pearl River, New York).

Following isolation, the animal is introduced to the test situation. This involves learning to walk with the handler and in the case of larger animals moving out of the home cage into a transfer cage and from there into the test chamber. If the research is eventually to take place in a restraint chair, similar adaption to this type of restriction is also required. Behavior of this type should be rewarded with fruit since it provides excellent means for the animal and handler to establish rapport with one another. If this procedure appears to be superfluous, and indeed may be when working with monkeys or other animals, it is highly essential to the chimpanzee experiment. In fact, it is recommended as an integral part of all pre-experimental procedures with the chimpanzee.

2 The 250 cc Pabulum Supplement recommended by the Veterinary Staff of the USAF Aeromedical Research Laboratory at Holloman AFB, New Mexico, consists of 4 oz. condensed milk, 1/2 egg, 1/8 pkg strawberry jello, 3 teaspoons salad oil, 1 oz. pabulum, 1 teaspoon Vita King multiple vitamins.

After approximately a week of this regimen, experimentation can begin. In most operant research, if an animal is to receive food reinforcement, he is usually deprived of food until he reaches 80 percent of his normal body weight. While several experimenters report the use of this technique with chimpanzees, it is usually reserved for other animals. With the chimpanzee, a day or two of food deprivation is usually sufficient before beginning magazine training. This, like many of the other techniques which are rigidly defined for lower animals, is quickly accomplished with the chimpanzee. For example, it is customary to train a food-deprived mouse to the food magazine for several days before introducing the operandum. Such a procedure can be handled in a matter of hours with a hungry chimpanzee. Hand-shaping of the lever pressing response can be accomplished quickly with the chimpanzee by what SKINNER has called the 'method of successive approximation'. In this technique, all responses near the lever are rewarded by the experimenter's activation of the food dispenser. Arm and hand movements remote to the lever are not rewarded. This same technique has been used with water reward and is particularly effective when training the animal to avoid an electric shock [FARRER and GRUNZKE, 1964].

In this regards, it should be pointed out that the superior transfer ability of the chimpanzee has dictated that the best approach to shock avoidance training is to train the subject to respond for positive reinforcement first. When this is mastered, avoidance tasks are learned quickly and performed with considerably less emotional trauma.

These procedures which are described in greater detail by PEGRAM and BOGO [1963] should be tailored to the individual animals and where these preliminaries may be omitted with other species their conscientious use in the case of the chimpanzee is strongly recommended. When these are followed, the experimenter can readily demand the more complex behavior of the operant conditioning schedules.

### *Operant Behavior*

SKINNER [1938] refers to two types of conditioning: *Respondant* conditioning which is more commonly known as classical or Pavlovian conditioning and *operant* conditioning. Within this classification almost all of the current behavioral experiments can be said to be of the operant type, however, for purposes of discussion, operant conditioning will be considered to include behavior that employs schedules of reinforcement and uses response

rate and patterning as dependent variables [KELLEHER, 1966; VERHAVE, 1966].

Within the framework of these criteria, SKINNER [1956] is quick to point out that the response rates and patterns on simple reinforcement schedules are pretty much the same regardless of species, and cites as examples, behavior on a multiple fixed interval-fixed ratio schedule by a pigeon, a rat, and a monkey. This fact, coupled with the superior cognitive ability of the chimpanzee has resulted in little if any operant research which could be classified as simple. Instead it involves complex multiple schedules that are commensurate with the skills of this species.

### *Avoidance Behavior*

In 1953, SIDMAN developed an avoidance conditioning schedule for rats which since has been used quite successfully with primates. In this schedule brief shocks are administered to the subject at regular intervals until the animal presses the lever. When this occurs the shock is delayed for a specified length of time. The time between the delivery of the shocks is called the shock-shock or S-S interval and usually lasts 3 sec; the time that each response delays the shock is called the response-shock or R-S interval and various investigators have employed a 15 and 20 sec R-S interval effectively with chimpanzees. CLARK [1961] used an R-S interval of 20 sec and within a very short period of time a young chimpanzee developed a high response rate and received very few shocks. Similar behavior by chimpanzees was also reported by FERSTER [1958a] in what represented one of the first attempts to control this species with electric shock. In his study he demonstrated that the chimpanzee would develop a high response rate on a SIDMAN avoidance schedule when it was accompanied by a postponement of a time-out period from a schedule involving positive reinforcement.

BELLEVILLE, ROHLES and GRUNZKE [1960] trained a chimpanzee on the SIDMAN, or as they called it, a continuous avoidance schedule but added a discrete avoidance component. These combined tasks, which were performed by the chimpanzee during the Mercury-Redstone space flight [ROHLES, GRUNZKE and REYNOLDS, 1963] involved 2 lights and 2 levers. In the presence of a red light, the subject had to press the right lever at least once every 15 sec (R-S interval) in order to avoid shock, and responses slower than this resulted in the delivery of a shock every 3 sec (S-S interval). At the same time as the subject was performing the continuous task, a blue light came on above the



left lever at random intervals, and when this occurred, the subject had 5 sec in which to press the left lever in order to avoid shock. For the discrete component, the response latency, that is, the time between the presentation of the blue light and the response to the left lever which turned it off was about 0.7 sec.

FARRER and GRUNZKE [1964] have reported that in the course of training a chimpanzee on a continuous avoidance schedule, fewer shocks will be received if the subject learns a discrete avoidance task first than if the continuous avoidance is learned initially by itself. Incidentally, it should be pointed out that once a chimpanzee is trained on an avoidance schedule, whole weeks may elapse without the delivery of a single shock – behavior which is not common to other species.

FINDLEY and AMES [1965] used the discrete avoidance task somewhat differently and certain aspects of their experiment is worthy of note. First, a 0.5 sec 5–7 m.a. shock was delivered through a collar that the subject wore around his neck and secondly, behavior was recorded continuously for an experimental period of 60 days duration. Two discrete avoidance tasks were used: When a white light was turned on behind the lever the subject had to press the lever within 15 min to avoid shock. When this occurred the light was turned off for 15 min before coming on again. The second discrete avoidance task was performed on the same lever and was signalled by the illumination of a blue light. When this light came on, the subject had 15 sec to press the lever to avoid shock and, each response turned off the light for 15 sec. At the same time as the subject was performing this task, a 4 h FI contingency was programmed on a second lever and the first response after 4 h turned off the avoidance cue light and was reinforced with an 8 h time-out. Following this period, the animal was alerted to perform by the ringing of a door bell and if the 15 min avoidance task had been programmed for the previous 4 h session, the 15 sec task went into effect – the two being in effect for alternate four hour periods. The results of this rather unique study showed that when the subjects were performing on the short 15 sec avoidance schedule, their corresponding rate on the FI schedule was high however, the opposite was true when the 15 min avoidance task was being performed. Also, the rate on the FI schedule tended to diminish as the experiment progressed.

The combined continuous and discrete avoidance tasks have also been used to assess the effects of increased acceleration on performance [FARRER, GRUNZKE, GILBERT, BARNHART and JACOBS, 1963; REYNOLDS, GRUNZKE and ROHLES, 1963] and in a study in which chimpanzee performance was

measured during exposures to 100% oxygen at sea-level atmospheric pressures [FARRER and REYNOLDS, 1962].

### *Multiple Schedules of Reinforcement*

The combined continuous and discrete avoidance schedule described above was combined with several other tasks and together they demonstrate the discriminative ability of the chimpanzee as well as his performance on a complex multiple schedule of reinforcement. The task was designed by BELLEVILLE, ROHLES, GRUNZKE and CLARK [1963] for the purpose of sampling a wide range of behaviors over a short period of time in a single chimpanzee, however, it was used by FARRER and BOGO [1962] to assess chimpanzee behavior on a simulated space flight of 3 days.

In this task the subject was trained in a chamber similar to the one shown in figure 3. Three In-Line Digital Displays were used to present the discriminative stimuli for the various component tasks and a lever was mounted below each display. For the first component, a red light was illuminated on the right display which served as the cue for a continuous avoidance task. When this schedule was in effect the subject had to press the right lever at least once every 10 sec (R-S 10 sec) to avoid shock; when the subject made this response, a white light flashed on the middle display as secondary reinforcement. At the same time as this task was being performed, a discriminated avoidance task was in effect which was cued by the illumination of a blue light on the left display. When this appeared, the subject had to press the left lever within 5 sec to avoid shock. This concurrent schedule was in effect for 10 min and was followed by a 2 min rest.

Following this, the second component was signalled by the illumination of a green light in the right display. When this occurred, the subject performed on a differential reinforcement low rate (DRL) schedule. The DRL reinforcement schedule, it will be recalled, requires the subject to space his responses in time. For example, if an animal on a DRL 10 schedule presses the lever at time zero and again at 10, 11, 12 etc. seconds later he would be rewarded. On the other hand, if his second response occurred 9 sec after his first, he would not receive reinforcement and would have to withhold his third response for at least 10 sec more to be rewarded. In this component of the multiple schedule a response which was made after a 10 sec waiting period turned on a light above a liquid feeder and when this light was on, biting the lip-lever drinking tube delivered 1 cc of water. When this chained

response occurred, the next 10 sec DRL period began. This component continued in effect for 10 min.

It should be noted that BOGO, REYNOLDS and ROHLES [1963] have described a rather unique approach to shaping a chimpanzee on a DRL operant conditioning schedule. After magazine training on a water feeder (see fig. 2), a green light on an In-Line Digital Display was turned on over a lever. When the subject pressed this lever, a second light on water dispenser came on which served to cue the animal that a drink could be obtained by biting the lip lever. When this response was made, both the panel light and dispenser light went off for 20 sec. When the subject was responding only to the illumination of green light over the lever, the length of time that the green light was on was extended in 9 increments. In other words, instead of the green light being turned off immediately after the subject took a drink; then it was turned off for 17 sec before coming on again. When the subject was responding only to the illumination of the green panel light which came on after the 17 sec rest, the length of time that the green light was on was increased until the light remained illuminated for 19 sec and was off for 1 sec. When the performance at these time periods became effective, the 1 sec 'time-out' period was eliminated. At this stage the animal was spacing his responses between 10 and 15 sec apart and responses which were spaced by 13 sec (mean response delay) were rewarded. This time was quickly increased to 20 sec and asymptotic, efficient performance is reported after 22 h of training - 2 h per day for 11 days.

The cue for the third component of the multiple schedule was the illumination of a yellow light in the middle display. This signalled a fixed ratio-50 schedule in which the animal had to press the middle lever 50 times for one 1-g food pellet. This component was in effect for 10 min and without a time out period was followed by 18 three-stimulus oddity problems. For each problem two of the stimuli were alike and one was different, and the subject was reinforced with a one gram food pellet for pressing the lever under the display which had the odd symbol. Incorrect responses were followed by a 15 sec time out and the problem was presented again. Only one set of 18 problems was presented during the 10 min period that this component was in effect, and following this period, all components were repeated in the same order. Representative performance on this task is shown in figure 5.

For the two orbit space flight, the oddity component was placed on a shock avoidance reinforcement schedule instead of a food reward contingency. In this variation, the animal was shocked if he failed to press the lever under the odd symbol or waited longer than 10 sec before making a response. It

should be noted that with a shock-avoidance contingency, the level of discrimination accuracy was not nearly so high as under positive reinforcement. An interesting event happened during this flight which contributes some light on the temperament and adaptability of the chimpanzee. On the first

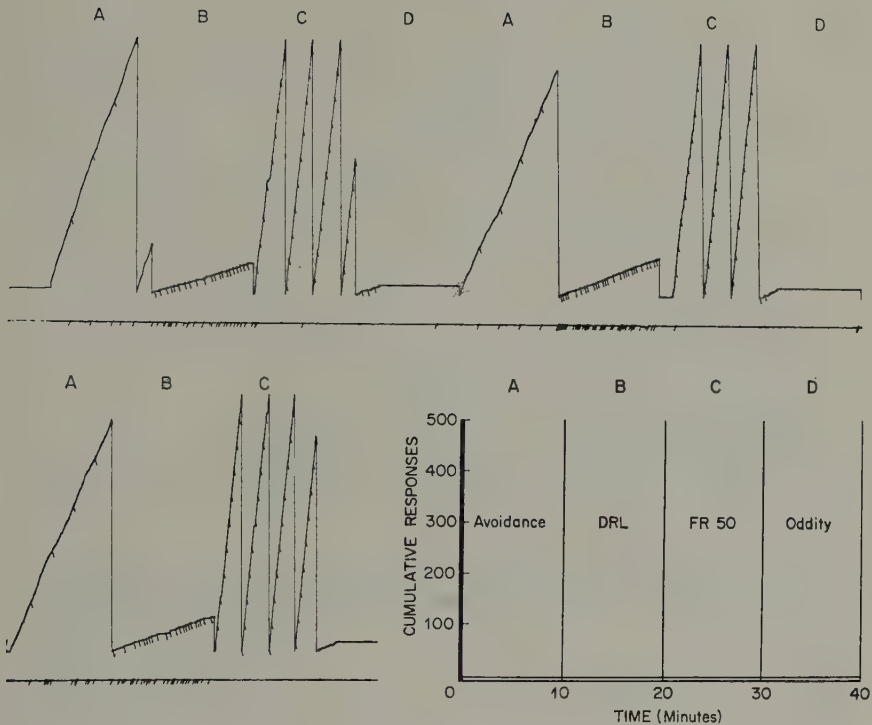


Fig. 5. Cumulative record showing three consecutive cycles of chimpanzee performance on an operant conditioning schedule. The pen reset to the bottom of the record when 500 responses had accumulated or when a new component went into effect. The recorder was off during the time-out periods. Component A (continuous and discrete avoidance) responses on the continuous avoidance task appear on the cumulative record – blue light presentations which are cues for the discrete task appear as pips on the lower (event) record. Component B (DRL) responses appear on the cumulative response record and presentations of the light on the water feeder appear as pips on the lower (event) record. Component C (FR 50) responses on the center record were accumulated and food reinforcements appear as pips. Schedule D (oddy) correct and incorrect responses appear on the cumulative record; incorrect discriminations appear as pips on the lower record [BELLEVILLE *et al.*, 1963] (see also fig. 3).



repetition of the schedule, the switch on the middle lever failed to operate, and while this merely placed the fixed-ratio component in an extinction condition, it presented an unsolvable problem for the oddity component since the first problem presented a circle, a triangle, and a circle on the left, middle, and right displays, respectively. This called for a response on the middle lever which it must be assumed, was made; however, because of the switch malfunction it resulted in the delivery of a shock. When the problem was presented again, the subject pressed the left lever and was also shocked. The same was true on the third presentation of the problem when he responded on the right lever. And this alternating between the right and left lever with, it must be assumed, several responses to the middle lever although they could not be measured, continued until the thirty-fourth presentation of the problem when the middle switch operated properly. Similar attempts using the alternation strategy was observed on the second and final repetition of the task, but more important, this completely novel situation, coupled with the insults of the space flight itself, in no way altered the subject's performance on the other components in the schedule [ROHLES, GRUNZKE and REYNOLDS, 1963].

Another complex multiple schedule designed to study chimpanzee performance during extended space flight has been developed by ROHLES, REYNOLDS, GRUNZKE and FARRER [1962]. The test panel which is shown in figure 6 consists of eight Stimulus-Response Keys (SRK), two one-inch diameter lights and three levers. A 1024-cps tone at 60 db is presented through a speaker mounted behind the top SRK on the panel. The tone is presented aperiodically for five seconds and when this occurs the SRK must be pressed within 5 sec in order to avoid shock. A blue light is mounted behind SRK's A through E (see fig. 6); these lights come on aperiodically in a random sequence and the subject has 5 sec to push the lighted SRK in order to avoid shock.

Both of these tasks, referred to as visual and auditory monitoring (AM and VM) were superimposed on two conventional operant conditioning schedules. The red light served to cue the subject that the continuous [SIDMAN] avoidance schedule was in effect and that lever 3 should be pressed at least once every 20 sec to avoid shock. At the same time that this was being performed, the blue light came on and when this occurred lever 1 had to be pressed within 5 sec to avoid shock. This task was performed for 7.5 min and was followed by a 3 min rest. After this rest period an FR cue light was turned on over lever 2 as a signal to press the middle lever on a Fixed ratio-50 reinforcement schedule. When the subject made 50 responses the FR cue light

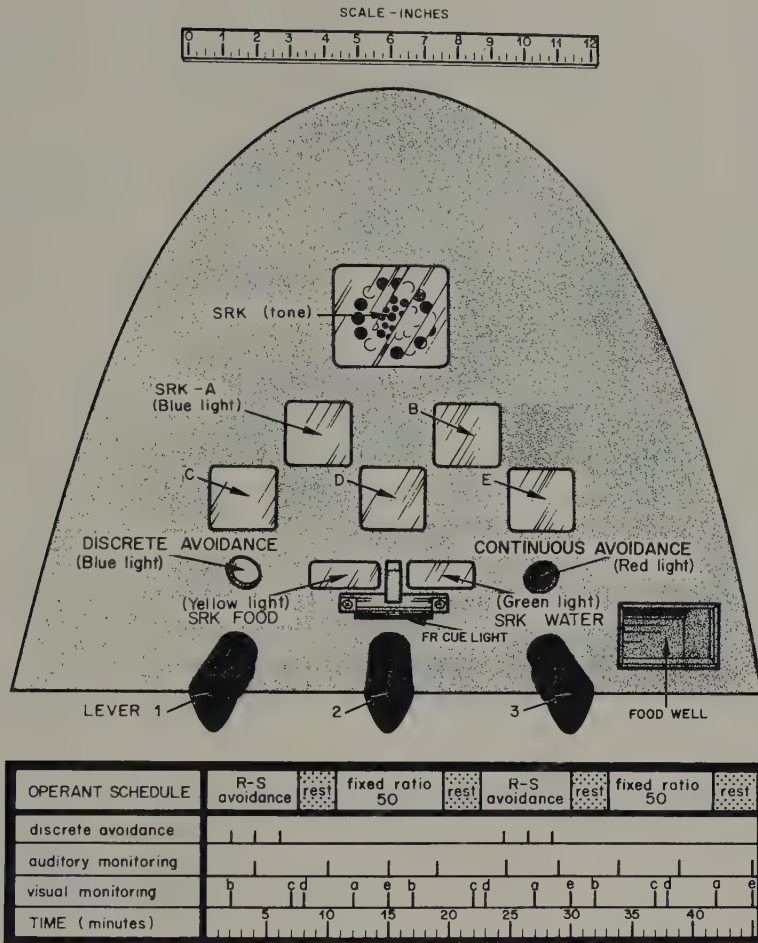


Fig.6. Performance panel for complex multiple operant conditioning schedule with discrete components [ROHLES *et al.*, 1962] (see also fig.2).

went off and the two SRK's above the cue light came on. Then if the subject desired food, he pressed the yellow (left) SRK and was reinforced with a one-gram food pellet; if, however, water was desired a response to the green (right) SRK illuminated a light on the water feeder to cue the subject that water was available and would be delivered by biting the lip-lever drinking tube. This program was in effect for 9 min and was followed by a 3 min

'time-out'. It should be noted that this schedule has been quite effective for studying behavior following exposure to exotic rocket fuels [REYNOLDS, ROHLES, PRINE, CARTER and BRUNSEN, 1963] complex reaction time [REYNOLDS, HAY and PEGRAM, 1965] and rapid decompression [KEOSTLER, REYNOLDS, BARKER, CATONE and WILSON 1965; KOESTLER and BARKER, 1967] as well as chimpanzee performance during a simulated orbital flight of 8 days [REYNOLDS, GILBERT, BOGO and BARNHART, 1964]. The FR-50 schedule in which the subject could select either food or water reinforcement was used in an experiment to study the feeding rhythms in chimpanzees [ROHLES, REYNOLDS and GRUNZKE, 1963].

A variation on the multiple avoidance task was developed in another reinforcement schedule by REYNOLDS, BOGO and ROHLES [1963]. A chimpanzee was restrained in a chair containing a box with 3 In-Line Digital Displays each of which was centered above a lever. In the first component, a white cue light flashed momentarily to signal 'time zero' and at the same time a green light was illuminated on the right display. Then between 15 and 30 sec later, the subject had to press the right lever to avoid shock. Responses made before 15 sec had elapsed or failure to respond between 15 and 30 sec resulted in a 16-20 m.a. shock, however, when the subject avoided the shock by delaying his response by 15 sec, the green light was turned off for 15 sec. The test session lasted 15 min and the cue light was presented once every 45 sec during this period.

Following a rest of 5 min, the second component was performed which was signalled by the illumination of a red light in the middle display. When this came on, the subject had to press the middle lever 20 times within 20 sec in order to avoid shock. As the authors point out, reinforcement under this component is of two types. First, the subject can avoid shock by making 20 responses in 20 sec, but secondly, the faster the performance, the longer will be the time-out period which is added to the programmed rest period of 10 sec.

The third component in the schedule was a single discrete avoidance task which was superimposed on the second component. For this task a blue light was illuminated on the left display and the subject could avoid shock by pressing the left lever within 2 sec after this occurred.

This schedule which involves two types of timing behavior was performed by a chimpanzee without receiving a single shock. Moreover, performance on the second component requiring 20 responses in 20 sec showed a high and stable response rate with response latencies averaging 0.3 to 0.5 sec on the discrete task.

*Studies with Tokens as Reinforcers*

It is almost impossible to peruse a single text in Introductory Psychology, not to mention those in learning, comparative or animal behavior without discovering a reference to the now classic study by COWLES [1937] in which chimpanzees were rewarded with tokens which they could exchange for food. KELLEHER [1966] however, extended this study using operant conditioning reinforcement schedules and by doing so, developed three definitions to describe his research. The first was used to describe the behavior that occurs early in the experiment in which the animal is 'shaped' with food reinforcement to insert tokens into a slot which result in the delivery of a food pellet; this is called the *exchange*. In the next stage of training, the animal is shaped so that the delivery of a token is contingent upon a response such as pressing a lever. If the animal is required to retain the tokens for a specified time before the exchange is possible, this time period is known as the *exchange interval*; on the other hand, if the subject is required to obtain a specified number of tokens before affecting the exchange, the number of tokens he is required to save is called the *exchange ratio*.

In his first study, KELLEHER [1957a] reinforced chimpanzees with tokens for performing a Fixed Interval 5 (FI5) schedule, however, they could not exchange these tokens until they had accumulated a fixed number of tokens. This number, or the exchange ratio, was gradually increased from 2 to 3 and then to 4 and in all instances the responding was maintained at a constant level. However, when the exchange ratio was increased to 6, long pauses developed in the FI performance and stopped completely when the exchange ratio was increased to 8.

In a second study, KELLEHER [1958a] attempted to determine if performance for food tokens was contingent upon the number of tokens the animal had in his possession. For this he trained two chimpanzees on a Fixed Ratio 125 (FR 125) reinforcement schedule for one token reward, with an exchange ratio of 50. Under this condition, his animals usually paused more than two hours in some instances before starting to perform; however when the animals were given 50 tokens at the beginning of the session, performance began immediately, thus demonstrating that the number of tokens in the chimpanzee's possession was a powerful stimulus for controlling its behavior in the experimental situation.

This was not the case, however, when the subjects were performing on a multiple schedule. In this study [KELLEHER, 1957b], a token was presented when the chimpanzee performed on a Fixed Ratio 20 schedule in the presence



of a green stimulus light and also when the subject performed on a Fixed Interval 5 schedule when an orange light was illuminated. The exchange ratio was 60. The reason presented for the sustained performance on the multiple schedule which was lacking in the FI schedule alone was that the FR 20 component strengthened the FI component 'through generalization or induction'. It should also be noted that the FR component of the multiple schedule was 20 as compared to 125 in the earlier study and indeed, the author is quick to point out that high response rates can be maintained on a FR 20 schedule alone when the exchange ratio is 60 or FR 30 schedule with an exchange rate of 50 [KELLEHER, 1958a].

Although they did not use tokens, FINDLEY and BRADY [1965] used a flashing light as a conditioned reinforcer to enhance performance. In their study, a chimpanzee had to press a lever 4,000 times to extinguish a red light and thereby obtain 20 food pellets at one time from a hopper equipped with a flashing light. After the pellets were delivered, a green light was turned on and in its presence the same behavior was required and the identical reinforcement occurred, however, when the green light was on, a 0.5 sec a flash of light was presented at each 400th response or nine times before the final delivery of the 20 pellets. In this schedule, shorter pauses and working times were observed when the green light and associated intermittent flash were in effect then when the red light was on alone.

### *Concurrent Reinforcement Schedules*

In the studies involving concurrent reinforcement schedules with chimpanzees, the animal is confronted with two levers and is required to perform according to one reinforcement schedule on one lever and *at the same time* perform on a different reinforcement schedule on the second lever. FERSTER, in his analysis of chimpanzees on this schedule, emphasizes the fact that 'the chimpanzee, with its semierect posture and good hand dexterity ... could operate the two levers simultaneously (whereas) subprimates would have to alternate between the two keys' [FERSTER, 1957, p. 1090]. In FERSTER's first study [1957] all responses on the right lever were reinforced on a FR 120 schedule and responses on the left lever were reinforced on a Variable Interval 4 (VI 4) schedule, and his results showed that on the FR component, the rate was lower and more variable than when it was performed alone; and the brief bursts of responding on the VI schedule which are usually absent in a single component performance were in evidence in the concurrent schedule.

In his second set of experiments on concurrent schedules, FERSTER [1959] clearly demonstrates behavioral skills of the chimpanzee. The series of studies he conducted are presented in table II and aside from showing the step-by-step transition of one series of behaviors to the next, it demonstrates the variety and complexity of performance capable with the chimpanzee. More recent work on concurrent schedules has examined the problem of schedule preference, and HODOS and TRUMBULE [1967] conducted a series of studies to determine the strategies of schedule preference in chimpanzees.

*Table II.* Sequence of concurrent reinforcement schedules used with the chimpanzee  
[from FERSTER, 1959]

Order	Schedule for Left Lever	Schedule for Right Lever
1	VI 4	FR 150
2	VI 4	Multiple FR 150 FI 10
3	VI 4	Multiple FR 70 FI 10
4	VI 10	Multiple FR 70 FI 10
5	Extinction	Multiple FR 70 FI 10
6	Extinction	Multiple FR 70-475 FI 10
7	Extinction	Multiple FR 475 FI 10
8	VI 10	Multiple FR 475 FI 10
9	Extinction	Multiple FR 475 FI 10
10	VI 10	Multiple FR 475 FI 10
11	VI 10	Extinction
12	VI 10	Multiple FR 475 FI 10

### *Cognitive Behavior and Motor Skills*

Many studies have been conducted to assess the cognitive skills of the chimpanzee, but it remained for KELLEHER [1958b] to study them in the framework of the operant conditioning schedule. Two chimpanzees who had been trained to press a lever on an earlier experiment served as subjects, on two concept problems. Above the lever were 9 small plexiglass windows arranged in a  $3 \times 3$  matrix where 26 patterns, 13 positive and 13 negative were present-

ed successively. During the presentation of the positive pattern, a Variable Ratio 100 (VR 100) schedule of reinforcement was in effect, however, none of the responses was rewarded in the presence of the negative stimulus pattern. Positive stimulus patterns were terminated at reinforcement, however, the negative patterns remained illuminated until the subject had not pressed the lever for one minute. Representative positive and negative stimulus patterns are shown together with cumulative records on the VR tasks for 4 sequences in figure 7.

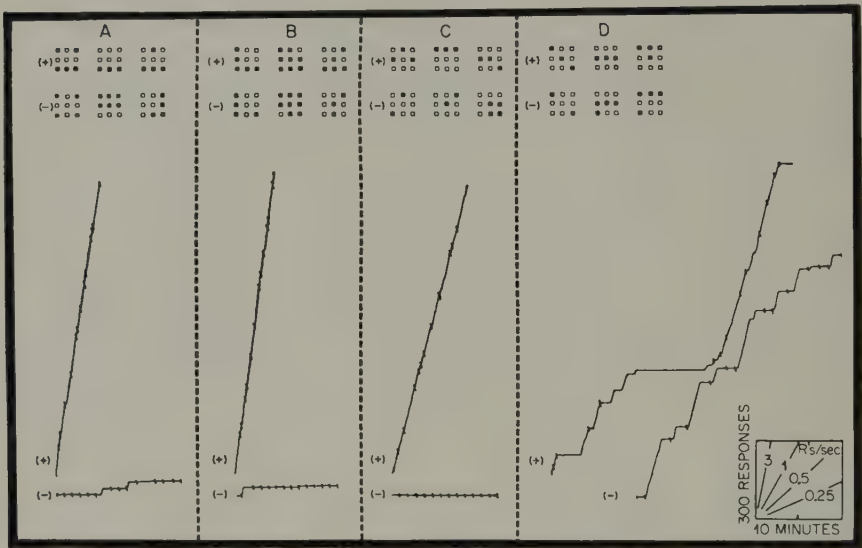


Fig. 7. Representative positive and negative stimulus patterns from each of four sequences are shown in the upper portion of each frame. Cumulative response records from each of the four sequences are shown in the lower portion. Pips indicate where stimulus presentation terminated [KELLEHER, 1958]. Fig. 7 is used with permission of the author (R. T. KELLEHER) and publisher, Science, The American Association for the Advancement of Science.

In the first problem, the positive patterns had a common element, namely, the illumination of the lower three windows; similar common elements were absent in the negative patterns. The cumulative records associated with these patterns, shown in Section A, demonstrate that the animals responded at a high rate in the presence of the positive patterns, but rarely responded at all when the negative patterns were presented. In addition, no change in performance was observed when the patterns were presented in a

new sequence or, as shown in Section B, when 6 new positive and negative patterns were presented without changing the concept.

In the second problem, the positive patterns contained 3 lighted windows whereas either 2 or 4 windows were lighted in the negative pattern. After approximately 15 h of training with these patterns it was found that the performance was not disrupted when the patterns were presented in a new sequence; however, when the patterns shown in Section C were changed to 6 positive and 6 negative patterns without changing the concept (Section D), performance was altered considerably.

Development of the oddity concept with 3 symbols, 2 of which are alike and one different has been discussed earlier, however, ROHLES [1961] found that he could develop an instrumental motor skill sequence in the chimpanzee if the order of the 18 3-stimulus oddity problems remained fixed and a

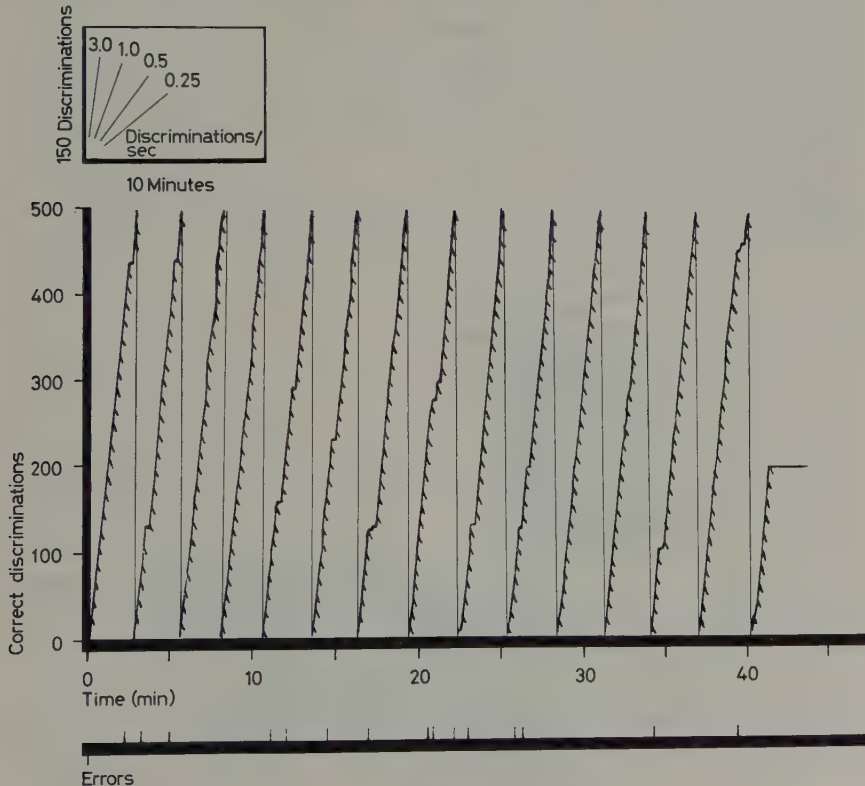


Fig. 8. Performance by a chimpanzee on an instrumental skill sequence. Pips on the cumulative record indicate reinforcements [ROHLES, 1961] (see also fig. 3).



ratio schedule was employed. Figure 8 shows the terminal performance of this 18 problem sequence when the ratio of correct discriminations to reinforcements was 19 (going through the series once and reinforcing the first correct discrimination on the second presentation). The extremely fast rate and accuracy illustrated shows that approximately 7,200 individual discriminations were made in 42 min with 15 mistakes.

Another motor skill task that has been studied with operant conditioning techniques is tracking [GRUNZKE, ROHLES, BELLEVILLE and WILSON, 1962]. The apparatus which is shown in figure 9 contained a vertical row of lights and a horizontal row of lights and two corresponding levers. The task required the subject to match a red light in the vertical row with a green light that moved by pressing the left (vertical) lever either forward or backward; then the red light on the horizontal row had to be matched with a green light by pressing the right lever either left or right. When the two rows of lights were matched, the subject pressed the third lever which presented a new pattern. When a fixed number of patterns was matched, the pressing of the third lever not only presented a new pattern but also delivered a reinforcement. High rates of performance have been obtained from a chimpanzee on a FR 7 reinforcement schedule.

A three dimensional tracking task was also developed by GRUNZKE [1963]. In this task a target in the form of a plus sign whose size changed

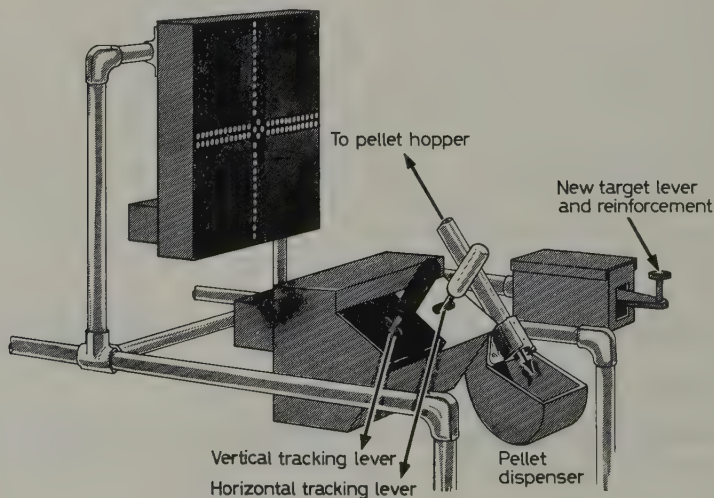


Fig. 9. Two dimensional tracking device for chimpanzee [GRUNZKE *et al.*, 1962].

continually, moved in an irregular pattern on a cathode ray tube. The subject could follow the target with a circle by moving one lever and change the size of the circle by moving a second lever. When the circle was adjusted in size to just enclose the target and the target was followed this way for a fixed time period, the subject was rewarded with a food pellet.

Another study of complex behavior in the chimpanzee was reported in a two lever problem by FERSTER [1958b] in which the subject had to perform the sequence of pressing the left lever three times followed by a single press of the right lever. Other presses of the right key resulted in a time-out of 10 sec and very accurate performance resulted when the ratio of correct sequences to reinforcements was increased to 33. A similar experiment designed to study counting behavior in the chimpanzee was conducted at the Holloman Air Force Base Aeromedical Laboratory by M. E. GRUNZKE [1963]. In this study the digits 1 through 7 appeared randomly in front of the chimpanzee on an In-Line Digital Display. If, for example, a 5 was presented on the display, the subject would have to press the counting lever 5 times and then a reinforcement lever for a food pellet; following this, a new digit would be presented. While somewhat inconclusive, the results showed that the subject could handle a task of this complexity with little difficulty.

An objective approach to the study of attention was suggested in a series of operant conditioning experiments with chimpanzees by KELLEHER [1958c]. The apparatus contained two levers, one a food-producing lever and the second an observing lever. In the presence of a dark stimulus panel, responses on a VR 100 schedule to the food-producing key sometimes were reinforced and sometimes were not, however, the subject could not determine whether reinforcement or extinction conditions were operating. When the subject pressed the observing lever, either a red light came on indicating that reinforcement conditions were in effect or a blue light came on which signalled extinction conditions were operating. Responses on the observing lever were maintained on a FR 60 reinforcement schedule with the rates being higher during reinforcement conditions than during extinction. Responses on the observing lever decreased to near zero when they did not produce the red or blue light, or when the discriminative stimuli (red and blue lights) were not correlated with reinforcement or extinction conditions.

Perhaps the most comprehensive study of all aspects of chimpanzee behavior in addition to his cognitive ability was done by FERSTER and his colleagues at the Institute for Behavioral Research. In their study, two chimpanzees pressed levers and pulled switches for *two years* to control their environment, learn arithmetic, and develop social interactions. As a result,

'An experimental paradigm different from the usual operant experiment ... emerged. (Traditionally) an animal is isolated in an environment (and) carefully restricted by use of a sound-resistant chamber in which he lives alone, (and is) influenced only by those events programmed by the experimenter. We did not isolate the animals, either visually or auditorily, from the non-experimental environment. Even when an animal was operating the experimental devices, he had visual access to the other animals in the cage and observers looking in, and could hear noises made in the laboratory or by the other animals in the experiment. Eventually, the animals 'sorted out' the stimuli in their environment in the manner of a multiple schedule. With a long history of experience in the experimental environment, the differential reinforcement, which occurs day in and day out with respect to the various kinds of stimulation, eventually brings the animals' behavior narrowly under the control of those stimuli related to the important reinforcers. The situation which finally evolves is similar to the normal environment in which a host of stimuli in a given situation exert no control over the individual's behavior because the important contingencies occur in respect to other events.'

'In general, the schedules and amount of reinforcement were arranged so that the animals maintained normal body weights and growth curves during the experiment without a regime of food deprivation or restriction in terms of body weights. Despite the limited deprivation conditions, it still proved possible to maintain substantial amounts of behavior and arrange contingencies as might be done under more stringent deprivation conditions. The cumulative development of successive repertoires was one of the reasons for designing a special environment for the animals different from the usual isolated experiment. Each successive experiment in the program depended upon a repertoire developed in an earlier experiment, so that it became essential that the animals be maintained under optimal conditions and in good health over a period of several years and possibly longer' [FERSTER and HAMMER, 1966, pp. 673-4].

#### SUMMARY

In considering the course of operant conditioning research with the chimpanzee, it immediately becomes apparent that the operant technique and the chimpanzee present two unique approaches to the study of behavior. At the outset, the chimpanzee, as FERSTER has shown, can be maintained without the necessity of a large medical support staff much in the same way as other primates are maintained in most university laboratories. But more important, the behavioral potential of this species is obviously, only beginning to be known. And when its study is approached from the standpoint of

operant conditioning with its automatic programming and recording techniques which now are compatible with high speed computers, the horizons for the scientific study of comparative behavior become unlimited,

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Author's address: Dr. FREDERICK H. ROHLES, JR., Institute for Environmental Research, Kansas State University, *Manhattan, KS 66502 (USA)*.

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# THE EVIDENCE FROM GENETICALLY INFORMATIVE MACROMOLECULES ON THE PHYLOGENETIC RELATIONSHIPS OF THE CHIMPANZEES

M. GOODMAN, G. WILLIAM MOORE, W. FARRIS and EMILY POULIK

Plymouth State Home and Training School, Northville, MI

North Carolina State University, Institute of Statistics

Biomathematics Program, Raleigh, NC and

Department of Anatomy, Wayne State University, School of Medicine, Detroit, MI

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## INTRODUCTION

It is well established that the genetic code resides in the deoxyribonucleic acid (DNA) polymers of the chromosomes and acts phenotypically by specifying the detailed structures of proteins. Thus comparisons of organisms in terms of the structural correspondence of either their proteins or their DNA polymers can provide relevant data for determining the degrees of genetic divergence among species. This chapter reviews the comparative protein and DNA data as they shed light on the phylogenetic relationships of chimpanzees.

Evolutionists and primatologists have long suspected a special relationship between the African apes and man. Indeed, DARWIN [1871] suggested that man's evolutionary origins occurred in Africa and that man's closest living relatives are the chimpanzee and gorilla. The mounting fossil discoveries of protohuman forms in Africa, particularly the Fayum apes [SIMONS, 1965], support this idea but do not rule out that the Hominidae arose from an ancestral ape species broadly distributed in Africa and Asia. Furthermore,

these new fossil discoveries are interpreted as giving evidence for the conventional view of an ancient (Oligocene) separation (28 or more million years ago) of Hominidae from Pongidae [SIMONS, 1967], with the latter family grouping *Pongo* with *Pan* and *Gorilla*. This traditional picture of hominoid phylogeny is a confused one, in which opinion varies as to whether the African apes are cladistically closer to man or to the orangutan, although the gorilla and chimpanzee are invariably represented taxonomically as if they were closer to the orangutan. Indeed the conventional classification [SIMPSON, 1945] often includes the gibbons as well as African apes in the Pongidae, thereby further obscuring the picture of hominoid phylogeny. The macromolecular evidence presented in this chapter depicts a closer genealogical relationship of the African apes to man than to the Asiatic apes and argues for a more recent descent of *Pan*, *Homo*, and *Gorilla* from a common ancestor than that traditionally portrayed.

#### AMINO ACID SEQUENCE DATA COMPARISONS OF THE CHIMPANZEE

Proteins are made up of long polypeptide chains, and for each different chain there is a specific gene (a segment of long chained DNA) which specifies in terms of its linear sequence of nucleotide bases the polypeptide chain's particular sequence of amino acid residues. The most common mutation in such genes are single base substitutions which result in single amino acid substitutions in the polypeptide chains which they control. Natural selection may cause certain of these point mutations to spread thru a population, and the number of such genetic code word changes will increase in an evolving gene as time passes with the protein product of this gene showing a proportionate number of amino acid sequence differences from its ancestral state.

Some of the best evidence that amino acid sequence replacements accumulate in a protein with the passage of time is provided by hemoglobin studies [ZUCKERKANDL and PAULING, 1965]. For example, the genetic variants of the hemoglobin polypeptide chains in different individuals within a species show an average of only one amino acid sequence difference between corresponding chains. Since a hemoglobin chain contains about 150 amino acid residues, the difference in genetic code words between the variant chains is less than 1%. Similarly, only minimal genetic code word differences occur among the homologous polypeptide chains in closely related species such as the sibling species of a genus. However, there are much greater differences among the homologous polypeptide chains in distantly related species. If



we compare human hemoglobin chains with those in horse, cattle, pig, and rabbit, we find, on the average, 22 sequence differences between the corresponding chains in the different mammals, a figure which represents 15% of the total number of residues coded by the hemoglobin genes [ZUCKERKANDL and PAULING, 1965]. Such comparative amino acid sequence data give concrete meaning to the concept that the longer two species have been separated in evolution, the more marked is the genetic divergence between them.

Theoretically it should be possible to map the phyletic relationships of contemporary species solely in terms of amino acid sequence data provided the sequences are obtained on enough different proteins to adequately sample the complete genetic codes or entire genomes of the various species under comparison. Such a genetic mapping of species relationships is a principal aim of the new field of molecular systematics. However, so far very little progress has been made in pursuing this aim, perhaps because the methods for isolating and sequencing proteins are very time consuming and difficult to execute.

The chimpanzee has been compared to other organisms with respect to the amino acid sequence homologies of two proteins: cytochrome C and hemoglobin. Chimpanzee cytochrome C consists of a single polypeptide chain of 104 amino acid residues, is identical in amino acid sequence to human cytochrome C, and varies by only one amino acid residue from rhesus monkey cytochrome C [unpublished observations of Dr. S.B. NEEDLEMAN, reported in MARGOLIASH and FITCH, 1968]. On the other hand, these catarrhine primate cytochrome Cs vary by at least 12 amino acid residues from each non-primate mammalian cytochrome Cs which has been analyzed such as that of dog, horse, donkey, pig, rabbit and kangaroo [FITCH and MARGOLIASH, 1967]. While suggesting that genetic correspondence among catarrhine lineages might be relatively high, these results reveal such extreme conservatism of cytochrome C in the Catarrhini that they do not provide any real clue on just how close the phyletic relationship is between *Pan* and *Homo*.

The comparative data on primate hemoglobins is much more extensive than that on the cytochrome Cs, but much less precise, since the amino acid sequences of many samples were not actually determined but were deduced from analyses of the amino acid compositions of peptide fragments produced by the fingerprinting or peptide mapping procedures of Ingram. In these deductions [e.g. HILL and BUETTNER-JANUSCH, 1964] the amino acid residues in the fragments are arranged to show the least number of sequence differences from the corresponding human peptide fragments of known amino

acid sequence. The data reviewed by ZUCKERKANDL [1963] and the unpublished data of Dr. W. KONIGSBERG on the amino acid sequence of chimpanzee hemoglobin chains [HILL, 1968] demonstrate for the major molecular forms of normal adult hemoglobin identity of chimpanzee to man and only two sequence or codon differences for gorilla. Orangutan hemoglobin diverges from these hemoglobins by at least several codon differences [HILL, 1968]. Somewhat more divergence is shown by gibbon hemoglobin and more yet by various old world monkey hemoglobins [HILL and BUETTNER-JANUSCH, 1964]. MATSUDA [1968] has recently found that rhesus monkey and human hemoglobins vary by four sequence differences in the alpha chain and by eight sequence or code word differences in the beta chain. These comparative hemoglobin data provide a piece of evidence for the view that the chimpanzee has a more recent common ancestry with man and gorilla than with the Asiatic apes or any other living primate.

#### IMMUNODIFFUSION SYSTEMATICS OF THE CHIMPANZEE

The degrees of structural correspondence between proteins in different species can also be determined immunologically by the cross reactions of antisera. Such cross reactions measure in a relative way the similarity between proteins with respect to amino acid sequences, for the antigenic sites (against which the antibodies are directed) are shaped by the amino acid groups exposed at a protein's surface. Thus, divergence at the antigenic level between a protein and its homologue in a different species is related to the number of code word differences in the corresponding genes.

There are now immunologic data on a series of proteins which shed light on the phyletic relationships of the chimpanzee. The largest portion of this data has been gained by an immunodiffusion technique utilizing modified Ouchterlony plates<sup>1</sup> for the species comparisons [e.g. GOODMAN, 1962a, 1963a,b, 1964, 1965, 1967, 1968; GOODMAN *et al.*, 1967]. Although the results obtained from such comparisons are qualitative in nature, they can on the basis of a simple mathematical logic be so processed in a computer as to clearly specify the degrees of antigenic relationship among the species in the comparison series [MOORE and GOODMAN, 1968a]. We describe below, pretty much as before [MOORE and GOODMAN, 1968a], the main features of our immunodiffusion computer approach to systematics and then present the

1 These plates can be obtained from Grafar Corporation, 12613 Woodrow Wilson, Detroit, Mich. 48238.

findings on the phyletic affinities of the chimpanzee obtained from processing the relevant Ouchterlony data in the computer.

*Nature of species comparisons in the modified ouchterlony plate.* A modified Ouchterlony plate when prepared for charging with immune reactants consists of either a Y or T arrangement of three wells bounded by plexiglas and in turn circumscribing a center field of agar (fig. 1). Antiserum prepared against a protein fraction from species 'h' (the homologous species) is placed in the bottom well, antigen preparation ( $A_1$ ) from a particular species (1) in the left well, and a corresponding antigen preparation ( $A_r$ ) from a different species (r) in the right well. One or two small filter paper pads saturated with distilled water are placed on the plexiglas; then the plate is fitted with a matching optically clear lid, and the junction between the plate and lid sealed with masking tape. The charged, sealed plate is then placed in an enclosed cabinet for incubation at room temperature. The wet filter pads prevent drying out of the agar over the several day period during which the antibodies and antigens are allowed to diffuse into the agar and react with each other. In contrast to the usual Ouchterlony plate which permits radial diffusion of the antibodies and antigens in a fairly large area of agar, the design of the modified plate constrains the immune reactants to diffuse towards each other in a limited area of agar (in the range of 1 cm). This increases the concentration of the reactants and thus favors the maximal growth of precipitin lines. Furthermore, due to the thin depth of the agar (1 mm), high reactant concentrations are obtained with quite small volumes (0.01 to 0.04 ml) of the antiserum and antigen preparations.

If the antiserum is directed to a single protein of the homologous species (defined here as species h) and if  $A_1$  comes from this species (i.e. if  $1 = h$ ), then the precipitin line due to  $A_h$  will continue to grow after it meets the precipitin line due to  $A_r$ , provided  $A_r$  does not share with  $A_h$  all the antigenic sites to which there are antibodies. This extension of the precipitin line is called a spur, and it represents all those antigenic sites found in  $A_h$  but not found in  $A_r$ . The fewer antigenic sites that  $A_r$  shares with  $A_h$ , the longer the spur. Different degrees of spur size ranging from trace to very long can readily be distinguished, although differences in the magnitude of long and very long spurs cannot accurately be judged, due to the limited area of agar on the plate. Thus if two species each show a marked divergence from the homologous species, it is necessary to compare them to each other to determine which shows the greater divergence.

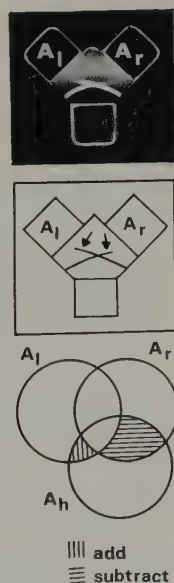
In contrast to a 'homologous comparison', in which  $A_1$  is from the

homologous species (i.e.  $l = h$ ), a 'heterologous comparison' employs antigens from species other than the homologous species in both antigen wells (i.e.  $l \neq h$  and  $r \neq h$ ). A spur formed by  $A_l$  against  $A_r$  indicates that  $A_l$  and  $A_h$  share certain antigenic sites not found in  $A_r$ . A spur formed by  $A_r$  against  $A_l$  on the other hand, indicates that  $A_r$  and  $A_h$  share certain antigenic sites not found in  $A_l$ . In some heterologous comparisons, a bilateral spur, such as is shown in figures 1, is formed, characterized by spurs against both  $A_r$  and  $A_l$ . In this situation,  $A_l$  and  $A_h$  share certain antigenic sites not common to  $A_r$ , and, in turn,  $A_r$  and  $A_h$  share certain antigenic sites not common to  $A_l$ . In order to deal with this most general of spur formations, we define the 'net spur',  $S_{lr}$ , formed by  $A_l$  against  $A_r$ , as the spur formed by  $A_l$  against  $A_r$  minus the spur formed by  $A_r$  against  $A_l$ .

From the size of the net spurs formed in certain comparisons it is possible to predict the results of other comparisons. This is illustrated in figure 2, which shows several comparisons in T type modified Ouchterlony plates developed with a rabbit antiserum to human transferrin (a purified protein from human serum used as the immunizing antigen). As can be noted, when the homologous antigen,  $A_h$  (human transferrin), is compared to  $A_2$  (gibbon transferrin), it forms a small net spur against  $A_2$ ; when compared to  $A_3$  (rhesus monkey transferrin), it forms a long net spur against  $A_3$ . Thus we may predict that

#### Set Theoretical Definition of the Net Spur

$$S_{lr} = N(A_l \cap A_h \cap A'_r) - N(A_r \cap A_h \cap A'_l)$$



*Fig. 1.* Photograph pictures a typical immunodiffusion comparison, with a schematic diagram beneath. Arrows indicate spurs. The Euler-Venn circle diagram shows how the spurs can be represented as overlapping sets of antigenic sites. The circle diagram is also expressed as an equation.



## Difference Property of Net Spurs

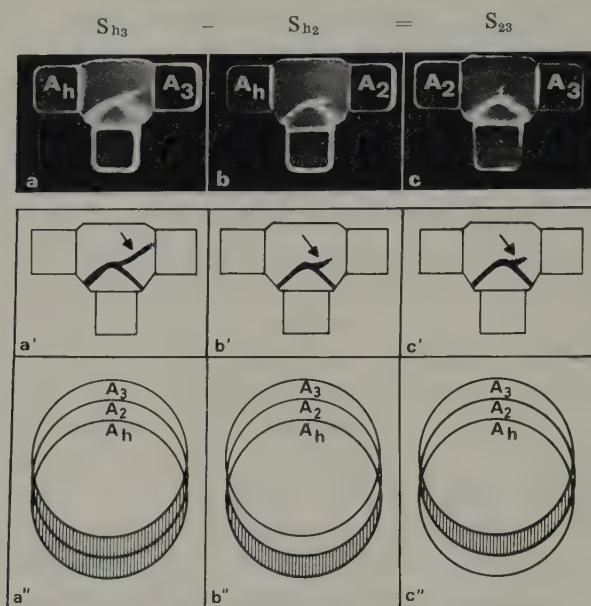


Fig. 2. Photographs picture three immunodiffusion comparisons in T shaped modified Ouchterlony plates, using rabbit anti-human transferrin as the antibody, which demonstrate the difference property of net spurs. Beneath lie schematic and circle diagrams as in figure 1. (a) Man versus rhesus monkey, net spur size 4. (b) Man versus gibbon, net spur size 2. (c) Gibbon versus rhesus monkey, net spur size 2. Observe that (a) - (b) = (c).

since  $A_3$  appears to share fewer antigenic sites with  $A_h$  than does  $A_2$ ,  $A_2$  should form a net spur against  $A_3$ . This is precisely what happens, for  $A_2$  forms a small net spur against  $A_3$  in a comparison of these two antigens. Indeed, the spur sizes have a difference property. Assigning values of 0 for no net spur (reaction of identity), 1 for trace net spur, 2 for small net spur, 3 for medium net spur, and 4 for long net spur, it can be noted that  $S_{h,3}$  (the net spur formed by  $A_h$  against  $A_3$ , having a value of 4) minus  $S_{h,2}$  (the net spur formed by  $A_h$  against  $A_2$ , having a value of 2) equals  $S_{2,3}$  (the net spur formed by  $A_2$  against  $A_3$ , having a value of 2).

*Set theoretical description of species comparisons.* The net spur,  $S_{1r}$ , represents those antigenic sites common to  $A_1$  and  $A_h$  but not to  $A_r$  minus those antigenic sites common to  $A_r$  and  $A_h$  but not to  $A_1$ . If  $A_h$ ,  $A_1$ , and  $A_r$  are con-

sidered as sets of antigenic sites, then the net spur,  $S_{1r}$ , is given by the expression

$$S_{1r} = N(A_1 \cap A_h \cap A_r') - N(A_r \cap A_h \cap A_1') \quad (1)$$

where, in the notation of set theory,  $\cap$  indicates intersection, ' indicates complement, and  $N$  indicates cardinality, i.e. the 'number of sites'. The difference property of spur sizes can be deduced directly from this definition of the net spur. Substituting and cancelling cardinalities of null sets, we have

$$\begin{aligned} S_{hr} - S_{h1} &= \{N(A_h \cap A_h \cap A_r') - N(A_r \cap A_h \cap A_h')\} \\ &\quad - \{N(A_h \cap A_h \cap A_1') - N(A_1 \cap A_h \cap A_h')\} \\ &= \{N(A_h \cap A_r') - N(A_h \cap A_1')\} \end{aligned} \quad (2)$$

Expanding the right side of (2) as cardinalities of disjoint sets, we have

$$\begin{aligned} &\{N(A_h \cap A_r') - N(A_h \cap A_1')\} \\ &= \{N(A_1 \cap A_h \cap A_r') + N(A_1' \cap A_h \cap A_r') - N(A_r \cap A_h \cap A_1') - N(A_r' \cap A_h \cap A_1')\} \\ &= \{N(A_1 \cap A_h \cap A_r') - N(A_r \cap A_h \cap A_1') = S_{1r}\} \end{aligned} \quad (3)$$

Hence,

$$S_{hr} - S_{h1} = S_{1r}$$

In other words, any net spur observed as data can be expressed as the difference between two homologous spurs. Using this principle, it is possible to write a set of simultaneous linear equations from which an estimated placement series can be solved from an arbitrary collection of net spur data. For example, the following set of average net spur data:

<i>Homo sapiens</i> :	h	$S_{h1} = 2.22$
<i>Pongo pygmaeus</i> :	1	$S_{h2} = 3.10$
<i>Hylobates lar</i> :	2	$S_{h3} = 3.50$
<i>Macaca mulatta</i> :	3	$S_{h3} - S_{h1} = S_{13} = 2.50$
		$S_{h3} - S_{h2} = S_{23} = 2.00$

will yield simultaneous linear equations of the form:

$$2 S_{h1} - S_{h3} = 2.22 - 2.50$$

$$2 S_{h2} - S_{h3} = 3.10 - 2.00$$

$$- S_{h1} - S_{h2} + 3 S_{h3} = 3.50 + 2.50 + 2.00$$

whose solutions are the estimated placement series:

$$S_{h1} = 1.9625$$

$$S_{h2} = 2.6525$$

$$S_{h3} = 4.2050$$

A computer program has been written in the PL/I computer language to perform these operations automatically on the IBM 360/75 computer at North Carolina State University at Raleigh and the IBM 360/65 computer at Wayne State University. This computer program employs magnetic discs for data storage and retrieval, and can handle up to 200 heterologous comparisons – i.e. solve 200 simultaneous linear equations – when the full capacity of the machine is used.

Furthermore, it can handle plate comparisons in which multiple precipitin lines form – such as when the antiserum is directed against whole serum and the antigen preparations are whole sera. In the case of multiple lines, the spur sizes formed by the several lines are averaged, weighted by the number of lines formed by the homologous species, and averaged into the single line data. The technique of making a weighted average allows multiple line data to be considered in terms of the more substantial contribution they make to the immune systematics of the species under comparison than do the single line data. A sample IBM coding form, which is capable of considering up to 11 lines per comparison, is illustrated in figure 3. The coding form has been filled out for the plate comparison pictured alongside.

As a first approximation, simultaneous equations such as those above are applied to all comparison data which are available. However, due to the geometrical limitations of the modified Ouchterlony plate, certain comparisons, recorded as giving very long spurs, may actually have been longer had they not been truncated by the edge of the agar field. As a step in the refinement of the initial estimates, all actual comparisons between species which show a difference value greater than 6 as a result of the first solution of the simultaneous linear equations are removed from consideration, and

the simultaneous equation technique is again applied to the remaining comparisons. This step is reiterated until all such erroneous  $S_{1r}$  values are removed. The final scale of ascending 'homologous spur sizes' indicates increasing divergence among the various heterologous species from the homologous species. It is also possible to equalize all scores in single comparisons above an arbitrary cut-off point (for example, scores between 4 and 6 can all be set equal to 4), so that the inaccuracy of judging the longer spur sizes is minimized.

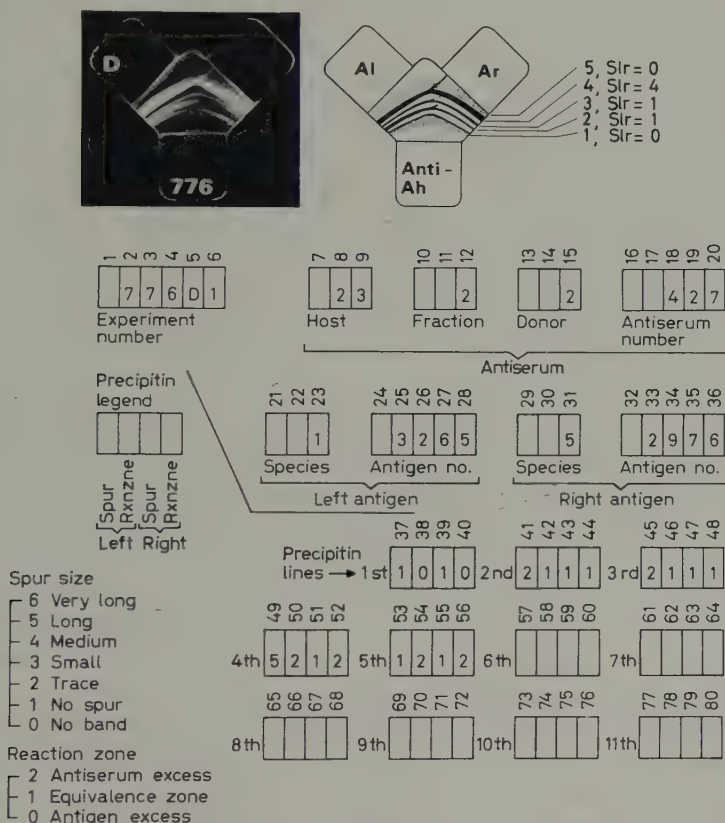


Fig. 3. Results of a comparison between human serum and orangutan serum in a Y shaped modified Ouchterlony plate, developed by a vervet antiserum to plasma (2 in our coding scheme for antigen fractions) from chimpanzee, and recorded on an IBM immunodiffusion coding form. Code numbers used for species are: 23 = *Cercopithecus aethiops*, 2 = *Pan troglodytes*, 1 = *Homo sapiens*, and 5 = *Pongo pygmaeus*. Alongside the coding form is a photograph of the actual comparison and a diagrammatic representation of the precipitin lines in this comparison.



*Species placement series from anti-hominoid sera.* Over 4,300 comparisons have been carried out in modified Ouchterlony plates using 148 chicken, rabbit, and monkey antisera to antigens (either purified proteins or whole serum or plasma) from the different hominoid species. In most cases the test antigens were whole sera and these were used at dilutions in which the concentration of the antigens were roughly equivalent to that of the antibodies, i.e. the precipitin reactions recorded in terms of net spur sizes occurred neither in marked antigen nor marked antibody excess. At least 43 different sera from *Homo sapiens*, 57 from *Pan troglodytes*, 2 from *Pan paniscus*, 16 from *Gorilla gorilla*, 20 from *Pongo pygmaeus*, 25 from *Hylobates lar*, 2 from *Hylobates pileatus*, and one from *Symphalangus syndactylus* were used as test antigens during the course of the study. The data of these 4300 plate comparisons have been coded and processed on the IBM 360/65 computer at Wayne State University by our program for calculating species placement tables from net spur sizes. The results are shown in tables I thru XXII. The species placement score given to five decimal points in the computer print outs have been rounded off to two decimal points, except in tables IX and X in which the five decimal point scores are used for further calculations.

In gathering the data, the net work of comparison was often guided by the generic classification of the serum specimens rather than the species classification. In other words, a hominoid serum may have been compared to a macaque serum (e.g. from *Macaca mulatta*) and a different macaque serum (e.g. from *Macaca irus*) compared to a ceboid serum. Thus in processing the data advantage was taken of a grouping statement in our program which allows us to place members of different species in the same group if we so chose. The data obtained with each type of antigen (e.g. the chicken antisera to human serum albumin) were first processed without specifying groups, in which case each species constituted a separate group. If in this data more than one species belonged to the same genus, each such species set was specified in a grouping statement and then the program was rerun on the same data. Most of the tables shown here are from the computer print outs of data processed with these grouping statements. However in processing the comparison data obtained with antisera to *Pan troglodytes* serum, *Pan paniscus* was not grouped with *P. troglodytes*, the homologous species, since an object of the comparisons was to determine the degree of relationship between these two chimpanzees.

The species placement series from the results obtained with chicken, rabbit, ceboid, and cercopithecoid antisera to chimpanzee (*Pan troglodytes*) serum are shown in tables V, XV, XVI, XIX, XX, and XXII. These demon-

strate that the chimpanzee barely diverges if at all from the pigmy chimpanzee, *Pan paniscus*, slightly diverges from man and gorilla, and shows increasingly more marked divergence from orangutan, gibbons, cercopithecoids, and ceboids in the order mentioned. The placement series (tables I-IV, VI, IX-XIV, XVIII, XXI) in which *Homo sapiens* and *Gorilla gorilla* are the homologous species also demonstrate the close relationship of the African apes to each other and to man.

That these species placement tables can be used to make reliable statements not only on the ordinal relationships of the species in a comparison series but also on the relative magnitude of divergence between homologous and heterologous species is demonstrated by comparing our scales of species divergence to those produced by quantitative immunologic techniques. It was possible to do this with literature values for results obtained using rabbit antisera to human albumin [HAFLEIGH and WILLIAMS, 1966; SARICH and WILSON, 1966] and rabbit antisera to human transferrin [WANG *et al.*, 1968]. As seen in table IX the scale of species divergence from man calculated from the Ouchterlony results parallels closely the scales which can be constructed from the cross reactions of rabbit anti-human albumin sera measured quantitatively either by the precipitin technique [HAFLEIGH and WILLIAMS, 1966] or the micro-complement fixation method [SARICH and WILSON, 1966]. Similarly in the case of the rabbit anti-human transferrin results (table X) our scale closely parallels that produced by the quantitative radioimmune inhibition of precipitation procedure [WANG *et al.*, 1968]. Indeed the correlations are extremely high, with  $r^2$  values of 0.99, 0.98, and 0.97 respectively, on comparing the relative magnitudes of divergence or dissimilarity portrayed by our computer approach to that portrayed by the three quantitative procedures.

*Calculation of phylogenetic trees of hominoid species from anti-hominoid placement tables.* The final phase in our immunodiffusion computer approach to systematics is to express the collection of calculated homologous spur sizes between contemporary species, such as those shown in the chicken anti-hominoid placement tables, into a branching arrangement of successively more inclusive common ancestors, until the final common ancestor subsumes all contemporary species. We consider the homologous spur size as an index of noncorrespondence between species (the size of this spur increases as two species share a smaller portion of the antigen in common), and to assume that smaller levels of antigenic correspondence indicate greater distance of common ancestor. We also assume that no more than two distinct sublineages of

a particular ancestor break apart at the same time. We do *not* have to assume that the homologous spur size is precisely proportional to the time of ancestral separation, only that there is a strictly increasing relationship between time and homologous spur size. These assumptions can accordingly be used to show [mathematical proof in MOORE and GOODMAN, 1968 b] that if two, disjoint subcollections of organisms are separated from a larger set, and the difference of the average *between* subcollections homologous spur size is calculated, then this difference will have a maximum value for the particular pair of subcollections which represent more recent common ancestries than in the collection as a whole. Repeated use of this technique on successively more recently ancestral collections of species can be used to generate a complete phylogeny from an arbitrary collection of homologous spur sizes.

In summary, a large spectrum of general net spur sizes can be reduced to numerical values using a set theoretical model; these can be further reduced to averaged homologous spur sizes via simultaneous linear equations, and the homologous spur sizes reduced to a phylogeny by partitioning the collection to yield each time the maximal between subcollection average homologous spur size. Applying this technique to the net spur sizes obtained from the chicken antisera prepared against human purified proteins, and chimpanzee, gorilla, orangutan and gibbon serum proteins and normalizing the hominoid values in each placement table with respect to the averaged old world monkey results taken as an arbitrary fixed net spur size of three, we obtain the phylogeny illustrated in figure 4.

In calculating the gibbon branch averaged results from *Hylobates lar* and *Symphalangus syndactylus* were used. Observe that the most distant common

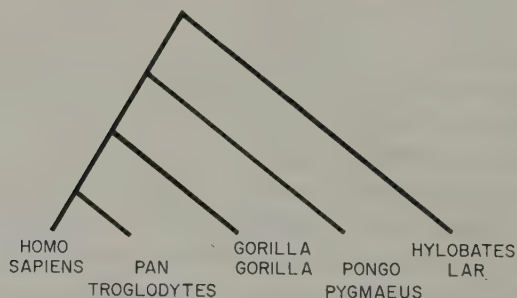
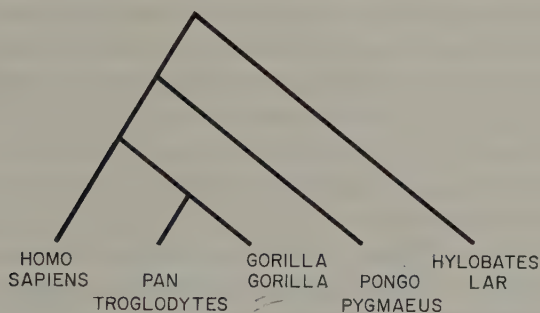


Fig. 4. Final phylogenetic tree resulting from chicken antisera prepared against purified human proteins and whole sera or plasmas from chimpanzee, gorilla, orangutan, and gibbon; also from vervet antisera prepared against human and chimpanzee plasmas.

ancestor separates this gibbon branch from the remaining four species, while the next most distant common ancestor separates the orangutan from man, chimpanzee, and gorilla. Among these remaining three species, chimpanzee and man appear to have a more recent common ancestor to one another than they do to gorilla. The data used to make this final conclusion, however, vary only within the measurement error of the spur technique, so that the possibility of a gorilla-chimpanzee or a man-gorilla most recent common ancestor cannot be overruled.

Indeed incomplete sets of rabbit anti-hominoid and new world monkey anti-hominoid placement tables yield the phylogeny with the chimpanzee-gorilla most recent common ancestor shown in figure 5. On the other hand, the old world monkey anti-hominoid placement tables are consistent with the tree generated by the chicken anti-hominoid data in which man and chimpanzee have the most recent common ancestor.



*Fig. 5.* Final phylogenetic tree resulting from rabbit antisera prepared against purified human proteins and whole sera or plasmas from chimpanzee and gibbon; also from ceboid antisera to human and chimpanzee sera.

#### TIME SCALE OF HOMINOID BRANCHING

The idea that there is a general relationship between increasing time of ancestral separation and increasing degree of antigenic divergence between species suggests that the phylogenetic trees calculated in the preceding section can be given a time dimension. We follow here the lead of SARICH and WILSON [1967] who used the index of dissimilarity (ID) values among primate albumins determined by the microcomplement fixation procedure.

Interpreting the scanty fossil evidence in relation to their immunologic findings, SARICH and WILSON [1967] suggested that the hominoid and cer-



copithecoid ancestries split about 30 million years ago. Taking the log ID as approximately proportional to the time (T) of divergence of any two species, i.e.,  $\log ID = kT$ , where k is a constant, they have the log of the mean ID observed between albumins of old world monkeys and hominoids correspond to a T value of 30 and solve for k. Then substituting the ID values between the albumins of the different living hominoids in their equation, they calculated that the chimpanzee-man, gorilla-man, and chimpanzee-gorilla ancestral divergences occurred at about the same period 5 million years ago. Then they calculated that the orangutan ancestry separated from the chimpanzee, man, gorilla ancestry about 8 million years ago, and that the divergence of the ancestral gibbon and siaming lineage from that leading to the other apes and man was 10 million years ago.

The traditional view of hominoid phylogeny [e.g. LE GROS CLARK, 1959] conflicts with that of SARICH and WILSON [1967] in depicting much more ancient ancestral separations of the living hominoid types and in placing these separations closer to the original split between Cercopithecoidea and Hominoidea. The separations within the Hominoidea of the lineage leading to the gibbons is placed in the Oligocene and the split between the lineages leading to the other living apes and man are usually placed in the late Oligocene or early Miocene, 20 to 30 million years ago. Even if SARICH and WILSON [1967] had assumed, more in accordance with the traditional view, that the hominoid and cercopithecoid ancestries split about 45 million years ago, their albumin ID data would still place the divergence of the gibbons from the other hominoids at only about 15 million years ago, the divergence of the lineage leading to orangutan at about 12 million years ago, and the splitting of the lineages leading to chimpanzee, gorilla, and man at about 7.5 million years ago, well into the Pliocene. However such time scales for the branching of the hominoid tree from the albumin ID data do not disprove the traditional view, in which much older ancestral separations are portrayed, for the rate of evolution of a single protein does not necessarily reflect in a proportionate manner the rate of evolution of the total genome.

There is reason to suspect that albumin evolution markedly slowed down in the lineages leading to the living hominoids [GOODMAN, 1962a, 1963a, 1965]. Thus the time scale for the splitting of these lineages calculated from albumin data alone might be grossly abbreviated, even though the data were gathered by the highly discriminating microcomplement fixation technique which is exceptionally sensitive to small antigenic differences. On the other hand, the degrees of divergence between hominoid species shown in our spur size placement tables (I-XXII) are based on a wider spectrum of pro-

teins. Possibly, the aggregate of these spur size measurements can reflect in a more proportionate manner the genetic distances between hominoid species.

The time dimension for the hominoid phylogenetic trees (fig. 4, 5) calculated from the spur size placement tables (I-XXII) is shown in table XXIII. In estimating the time of branching we assume linearity between time and spur size distance and use as did SARICH and WILSON [1967] a value of 30 million years for the time of divergence between hominoids and old world monkeys. The time distances among chimpanzee, gorilla, and man calculated from the chicken and rabbit antisera data are unreasonably small and much less than that calculated from the new and old world monkey antisera data. We suspect that the very small number of differing antigenic sites among the African apes and man were largely not distinguished by the spur size data of the rabbit and chicken antisera. Perhaps in these antisera the small proportion of antibodies to such rare sites were in many instances below the concentration threshold which allows spurs to develop. This would not be the case for precipitating antisera produced in monkeys, since these host animals, as close phylogenetic relatives of the donor animals, would be immunologically tolerant to the phylogenetically older sites on hominoid proteins and would have to respond largely to the newer antigenic sites which differ among hominoids.

Thus we date the divergence of the lineages leading to *Pan*, *Homo*, and *Gorilla* from only the ceboid and cercopithecoid antisera results and find this time to be about 6 million years ago. For the separation of the *Pongo* branch from the *Homo*, *Pan*, *Gorilla* branch we average the results of all antisera (chicken, rabbit, ceboid and Cercopithecoid) and estimate it to be about 14 million years ago. Finally we calculate from the chicken, rabbit, and ceboid antisera results that the most ancient split within the Hominoidea, that between the gibbons and the other hominoids occurred about 18 and a half million years ago. Although our spur size data on a spectrum of proteins agrees with the albumin data of SARICH and WILSON [1967] on the relatively recent descent of chimpanzee, man, and gorilla from a common ancestor, it yields more ancient separations for the other hominoid branches.

Yet another set of macromolecular data have been gathered which allow genetic distance between hominoids to be calculated and converted into a time scale. This data [MARTIN and HOYER, 1967] was obtained by the DNA hybridization technique [BOLTON and MCCARTHY, 1962; MCCARTHY and BOLTON, 1963; HOYER, MCCARTHY, and BOLTON, 1964] which measures the sharing of common polynucleotide sequences between animals. However recent work of BRITTEN and KOHNE [1968] shows that about half the genome

of a higher organism is made up of polynucleotide families in which similar sequences are repeated from a thousand to a million fold, and it is only these repeating portions of the genome which are involved in the interspecies comparisons. In addition the DNA fragments used in the hybridization technique can, if one chooses, be separated prior to use into adenine plus thymine (AT) and guanine plus cytosine (GC) enriched fractions. With unfractionated DNA fragments and with the AT and GC enriched fractions, MARTIN and HOYER [1967] compared human DNA to chimpanzee, gibbon, and rhesus monkey DNAs. Table XXIV shows the percentage of polynucleotide sharing between man and each of the three other primates revealed by the comparisons and the times of ancestral separation calculated from these percentages. Again the time of ancestral divergence between man and rhesus monkey is arbitrarily set at 30 million years. In terms of this value the man-gibbon divergence averages at 19 to 20 million years and the man-chimpanzee divergence at about 8 million years.

The time of divergence of the gibbon branch from the hominoid tree, whether calculated from the degree of non-matching polynucleotide sequences or from non-matching antigenic sites on proteins, can be accommodated to the traditional view, particularly if we assume in accordance with this view that the lineages leading to living hominoids and old world monkeys split in the Eocene, perhaps about 45 million years ago. Then both the DNA hybridization data and spur size protein data would put the gibbon-man most recent common ancestor in the Oligocene, about 29 million years ago. However the chimpanzee-man-gorilla most recent common ancestor would still be no older than 9 to 12 million years, an age considerably more recent than that proposed from interpretation of the present fossil record [e.g. SIMONS, 1967]. At this stage of our knowledge the actual time scale for the sequence of phylogenetic branching in the Hominoidea can not be decisively determined by either the molecular or fossil data. Ultimately, the problem of the time and sequence of hominoid phylogenetic branching will be solved as more data on primate macromolecules and fossils accumulate and as a better theoretical appreciation of the relationships between molecular and morphological evolution are achieved.

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Table I. Serological taxonomy ordered by increasing spur size  
chicken anti human albumin

<i>Homo</i>	<i>sapiens</i>	Man	0.00
<i>Gorilla</i>	<i>gorilla</i>	Gorilla	0.23
<i>Pan</i>	<i>troglodytes</i>	Chimpanzee	0.32
<i>Symphalangus</i>	<i>syndactylus</i>	Siamang gibbon	0.43
<i>Pongo</i>	<i>pygmaeus</i>	Orangutan	0.47
<i>Hylobates</i>	<i>lar</i>	Gibbon	0.87
<i>Hylobates</i>		Gibbon	0.87
<i>Aotes</i>	<i>trivirgatus</i>	Night monkey	3.06
<i>Macaca</i>	<i>irus</i>	Cynomologus monkey	3.27
<i>Macaca</i>	<i>nemestrina</i>	Pig-tail macaque	3.27
<i>Macaca</i>	<i>speciosa</i>	Stump-tail macaque	3.27
<i>Cynopithecus</i>	<i>niger</i>	Black ape	3.27
<i>Oedipomidas</i>	<i>oedipus</i>	Cotton-top marmoset	3.41
<i>Saguinus</i>	<i>fuscicollis</i>		3.41
<i>Tamarinus</i>	<i>graellsii</i>	Marmoset	3.41
<i>Cercocebus</i>	<i>galeritus</i>	Mangabey	3.45
<i>Papio</i>	<i>papio</i>	Baboon	3.46
<i>Papio</i>	<i>hamadryas</i>	Baboon	3.46
<i>Papio</i>	<i>sphinx</i>	Mandrill	3.46
<i>Presbytis</i>	<i>entellus</i>	Langur	3.52
<i>Cercopithecus</i>	<i>aethiops</i>	Vervet	3.61
<i>Erythrocebus</i>	<i>patas</i>	Patas monkey	3.61
<i>Theropithecus</i>	<i>gelada</i>	Gelada baboon	3.64
<i>Colobus</i>	<i>polykomos</i>	Colubus	3.65
<i>Callicebus</i>		Titi	3.80
<i>Saimiri</i>		Squirrel monkey	4.08
<i>Ateles</i>	<i>geoffroyi</i>	Spider monkey	4.14
<i>Ateles</i>	<i>fusciceps</i>	Spider monkey	4.14
<i>Ateles</i>	<i>belzebuth</i>	Golden spider monkey	4.14
<i>Tarsius</i>	<i>syrichta</i>	Tarsier	4.70
<i>Cebus</i>	<i>albifrons</i>	Capuchin	4.90



Table I. (Continued)

<i>Cebus</i>		Capuchin	4.90
<i>Tupaia</i>	<i>glis</i>	Tree shrew	5.45
<i>Cacajao</i>	<i>rubicundus</i>	Red-faced uakari	6.23
<i>Urogale</i>	<i>everetti</i>	Tree shrew	7.24
<i>Galago</i>	<i>crassicaudatus</i>	Bush baby	7.26
<i>Galago</i>		Bush baby	7.26
<i>Loris</i>	<i>tardigradus</i>	Slender loris	7.48
<i>Nycticebus</i>	<i>coucang</i>	Slow loris	7.51
<i>Perodicticus</i>	<i>potto</i>	Potto	7.64
<i>Arctocebus</i>	<i>calabarensis</i>	Angwantibo	7.80
<i>Elephas</i>	<i>maximus</i>	Asiatic elephant	7.95
<i>Loxodonta</i>	<i>africana</i>	African elephant	8.21
<i>Cynocephalus</i>	<i>volans</i>	Flying lemur	8.36
<i>Manis</i>	<i>pentadactyla</i>	Pangolin	8.56
<i>Propithecus</i>	<i>verreauxi coquerele</i>	Indus	8.68
<i>Lemur</i>	<i>fulvus</i>	Lemur	8.76
<i>Lemur</i>	<i>fulvus fulvus</i>	Lemur	8.76
<i>Lemur</i>	<i>fulvus albifrons</i>	Lemur	8.76
<i>Lemur</i>	<i>mongoz</i>	Lemur	8.76
<i>Atelerix</i>		African hedgehog	8.77
<i>Lasiurus</i>	<i>cinereus</i>	Hoary bat	9.21
<i>Petrodromus</i>	<i>sultan</i>	Elephant shrew	9.33
<i>Myotis</i>	<i>velifer</i>	Lone bat	9.33
<i>Bradypus</i>		Three-toed sloth	9.33
<i>Myrmecophaga</i>		Giant ant-eater	9.33
<i>Tapirus</i>	<i>terrestris</i>	Tapir	9.33
<i>Trichechus</i>	<i>manatus</i>	Manatee	9.33
<i>Bos</i>	<i>taurus</i>	Bovine	9.58
<i>Dasypus</i>	<i>novemcinctus</i>	Nine-banded armadillo	9.73
<i>Rattus</i>		Rat	9.75
<i>Rhynchocyon</i>		Elephant shrew	10.02

Table I. (Continued)

<i>Potos</i>		Kinkajou	10.13
<i>Canis</i>	<i>familiaris</i>	Dog	10.19
<i>Blarina</i>		Short-tailed shrew	10.30
<i>Procavia</i>	<i>capensis</i>	Hyrax	10.30
<i>Ursus</i>		Grizzly bear	10.30
<i>Eumetopius</i>	<i>jubatus</i>	Sea lion or stellar seal	10.30
<i>Didelphis</i>		Opossum	10.30
<i>Delphinopterus</i>	<i>leucas</i>	White whale	10.34
<i>Erinaceus</i>	<i>europaeus</i>	European hedgehog	10.36
<i>Tenrec</i>	<i>ecaudatus</i>	Tenrec	10.44
<i>Scapanus</i>	<i>townsendi</i>	Mole	10.71
<i>Oryctolagus</i>	<i>cuniculus</i>	Rabbit	10.96
<i>Macropus</i>	<i>rufus</i>	Red kangaroo	11.20
<i>Macropus</i>	<i>melanops</i>	Black-furred gray kangaroo	11.46
<i>Equus</i>	<i>equus</i>	Horse	11.66

Table II. Serological taxonomy ordered by increasing spur size  
chicken anti human transferrin

<i>Homo</i>	<i>sapiens</i>	Man	0.00
<i>Gorilla</i>	<i>gorilla</i>	Gorilla	0.12
<i>Pan</i>	<i>troglydites</i>	Chimpanzee	0.28
<i>Hylobates</i>	<i>lar</i>	Gibbon	2.20
<i>Hylobates</i>		Gibbon	2.20
<i>Symphalangus</i>	<i>syndactylus</i>	Siamang gibbon	2.35
<i>Pongo</i>	<i>pygmaeus</i>	Orangutan	2.36
<i>Cercocebus</i>	<i>galeritus</i>	Mangabey	2.83
<i>Erythrocebus</i>	<i>patas</i>	Patas monkey	2.87

Table II. (Continued)

<i>Papio</i>	<i>papio</i>	Baboon	2.87
<i>Papio</i>	<i>hamadryas</i>	Baboon	2.87
<i>Papio</i>	<i>sphinx</i>	Mandrill	2.87
<i>Cercopithecus</i>	<i>aethiops</i>	Vervet	3.14
<i>Presbytis</i>	<i>entellus</i>	Langur	3.15
<i>Macaca</i>	<i>mulatta</i>	Rhesus monkey	3.19
<i>Macaca</i>	<i>nemestrina</i>	Pig-tail macaque	3.19
<i>Macaca</i>	<i>speciosa</i>	Stump-tail macaque	3.19
<i>Macaca</i>	<i>radiata</i>	Bonnet macaque	3.19
<i>Cynopithecus</i>	<i>niger</i>	Black ape	3.19
<i>Theropithecus</i>	<i>gelada</i>	Gelada baboon	3.50
<i>Colobus</i>	<i>polykomas</i>	Colubus	3.55
<i>Saimiri</i>		Squirrel monkey	6.10
<i>Saimiri</i>	<i>sciurea</i>	Squirrel monkey	6.10
<i>Chiropates</i>	<i>satanus</i>	Saki	6.13
<i>Cebus</i>		Capuchin	6.30
<i>Lagothrix</i>		Woolly monkey	6.30
<i>Ateles</i>	<i>geoffroyi</i>	Spider monkey	6.30
<i>Ateles</i>	<i>fusciceps</i>	Spider monkey	6.30
<i>Ateles</i>		Spider monkey	6.30
<i>Saguinus</i>	<i>fusicollis</i>		6.30
<i>Tamarinus</i>	<i>graellsii</i>	Marmoset	6.30
<i>Aotes</i>	<i>trivirgatus</i>	Night monkey	6.45
<i>Cacajao</i>	<i>rubicundus</i>	Red-faced uakari	6.46
<i>Callicebus</i>		Titi	6.63
<i>Lemur</i>	<i>fulvus fulvus</i>	Lemur	9.62
<i>Lemur</i>	<i>fulvus albifrons</i>	Lemur	9.62
<i>Lemur</i>	<i>mongoz</i>	Lemur	9.62
<i>Galago</i>	<i>crassicaudatus</i>	Bush baby	10.10
<i>Galago</i>		Bush baby	10.10
<i>Galago</i>	<i>senegalensis</i>	Bush baby	10.10
<i>Nycticebus</i>	<i>coucang</i>	Slow loris	10.49
<i>Urogale</i>	<i>everetti</i>	Tree shrew	10.51

Table II. (Continued)

<i>Tupaia</i>	<i>glis</i>	Tree shrew	10.51
<i>Perodicticus</i>	<i>potto</i>	Potto	10.58
<i>Arctocebus</i>	<i>calabarensis</i>	Angwantibo	10.60
<i>Loris</i>	<i>tardigradus</i>	Slender loris	10.60
<i>Propithecus</i>	<i>verreauxi coquerele</i>	Indus	11.51
		Rabbit	12.30
<i>Zalophus</i>	<i>californianus</i>	California sea lion	12.51
<i>Manis</i>	<i>pentadactyla</i>	Pangolin	13.51
<i>Rattus</i>		Rat	13.51
<i>Delphinopterus</i>	<i>leucas</i>	White whale	13.51
<i>Dasybus</i>	<i>novemcinctus</i>	Nine-banded armadillo	13.84
<i>Loxodonta</i>	<i>africana</i>	African elephant	13.87
<i>Losiurus</i>	<i>cinereus</i>	Hoary bat	14.01
<i>Tenrec</i>	<i>ecaudatus</i>	Tenrec	14.01
<i>Scapomas</i>	<i>townseidei</i>	Mole	14.01
<i>Canis</i>	<i>familiaris</i>	Dog	14.01
<i>Rhynchocyon</i>		Elephant shrew	14.06
<i>Erinaceus</i>	<i>europaeus</i>	European hedgehog	14.26
<i>Petrodromus</i>	<i>sultan</i>	Elephant shrew	14.51
<i>Bradypus</i>		Three-toed sloth	14.51
<i>Myrmecophaga</i>		Giant ant-eater	14.51
<i>Equus</i>	<i>equus</i>	Horse	14.51
<i>Elephas</i>	<i>maximus</i>	Asiatic elephant	14.51
<i>Macropus</i>	<i>rufus</i>	Red kangaroo	14.51
<i>Didelphis</i>		Opossum	14.51
<i>Potos</i>		Kinkajou	14.61
<i>Atelerix</i>		African hedgehog	14.85
<i>Bos</i>	<i>taurus</i>	Bovine	15.05



Table III. Serological taxonomy ordered by increasing spur size  
chicken anti human gamma globulin

<i>Homo</i>	<i>sapiens</i>	Man	0.00
<i>Pan</i>	<i>troglodytes</i>	Chimpanzee	0.19
<i>Gorilla</i>	<i>gorilla</i>	Gorilla	1.02
<i>Pongo</i>	<i>pygmaeus</i>	Orangutan	1.29
<i>Symphalangus</i>	<i>syndactylus</i>	Siamang gibbon	1.98
<i>Hylobates</i>	<i>lar</i>	Gibbon	2.08
<i>Hylobates</i>		Gibbon	2.08
<i>Cercopithecus</i>	<i>aethiops</i>	Vervet	2.58
<i>Papio</i>	<i>papio</i>	Baboon	2.72
<i>Colobus</i>	<i>polykomos</i>	Colubus	3.19
<i>Macaca</i>	<i>mulatta</i>	Rhesus monkey	3.19
<i>Macaca</i>	<i>irus</i>	Cynomologus monkey	3.19
<i>Macaca</i>	<i>speciosa</i>	Stump-tail macaque	3.19
<i>Macaca</i>	<i>radiata</i>	Bonnet macaque	3.19
<i>Theropithecus</i>	<i>gelada</i>	Gelada baboon	3.19
<i>Presbytis</i>	<i>entellus</i>	Langur	3.38
<i>Ateles</i>	<i>geoffroyi</i>	Spider monkey	4.54
<i>Ateles</i>	<i>fusciceps</i>	Spider monkey	4.54
<i>Cebus</i>	<i>albifrons</i>	Capuchin	4.70
<i>Aotes</i>	<i>trivirgatus</i>	Night monkey	5.53
<i>Saimiri</i>		Squirrel monkey	5.68
<i>Oedipomidas</i>	<i>oedipus</i>	Cotton-top marmoset	6.15
<i>Tamarinus</i>	<i>leucopus</i>	Marmoset	6.15
<i>Tamarinus</i>	<i>graellsii</i>	Marmoset	6.15
		Rabbit	6.98
<i>Galago</i>	<i>crassicaudatus</i>	Bush baby	7.12
<i>Galago</i>		Bush baby	7.12
<i>Galago</i>	<i>senegalensis</i>	Bush baby	7.12
<i>Nycticebus</i>	<i>coucang</i>	Slow loris	7.53
<i>Bos</i>	<i>taurus</i>	Bovine	7.82
<i>Lemur</i>		Lemur	7.84

Table III. (Continued)

<i>Elephas</i>	<i>maximus</i>	Asiatic elephant	7.87
<i>Perodicticus</i>	<i>potto</i>	Potto	7.90
<i>Erinaceus</i>	<i>europa</i>	European hedgehog	8.05
<i>Tupaia</i>	<i>glis</i>	Tree shrew	8.70
<i>Rattus</i>		Rat	8.91

Table IV. Serological taxonomy ordered by increasing spur size  
chicken anti human ceruloplasmin

<i>Homo</i>	<i>sapiens</i>	Man	0.00
<i>Gorilla</i>	<i>gorilla</i>	Gorilla	0.11
<i>Pan</i>	<i>trogodytes</i>	Chimpanzee	0.16
<i>Presbytis</i>	<i>entellus</i>	Langur	1.77
<i>Colobus</i>	<i>polykomos</i>	Colubus	2.03
<i>Macaca</i>	<i>mulatta</i>	Rhesus monkey	2.03
<i>Macaca</i>	<i>speciosa</i>	Stump-tail macaque	2.03
<i>Macaca</i>	<i>radiata</i>	Bonnet macaque	2.03
<i>Papio</i>	<i>anubis</i>	Baboon	2.24
<i>Pongo</i>	<i>pygmaeus</i>	Orangutan	2.40
<i>Cercopithecus</i>	<i>aethiops</i>	Vervet	2.58
<i>Symphalangus</i>	<i>syndactylus</i>	Siamang gibbon	2.66
<i>Hylobates</i>	<i>lar</i>	Gibbon	2.83
<i>Aotes</i>	<i>trivirgatus</i>	Night monkey	4.66
<i>Ateles</i>	<i>geoffroyi</i>	Spider monkey	4.75
<i>Saimiri</i>		Squirrel monkey	4.75
<i>Nycticebus</i>	<i>coucang</i>	Slow loris	7.09
<i>Lemur</i>	<i>fulvus fulvus</i>	Lemur	7.97
<i>Bos</i>	<i>taurus</i>	Bovine	8.05
<i>Galago</i>	<i>crassicaudatus</i>	Bush baby	8.66
<i>Galago</i>		Bush baby	8.66

Table IV. (Continued)

<i>Tupaia</i>	<i>glis</i>	Tree shrew	11.52
		Rabbit	11.52
<i>Rattus</i>		Rat	11.52
<i>Erinaceus</i>	<i>europa</i>	European hedgehog	11.86
<i>Canis</i>	<i>familiaris</i>	Dog	13.52
<i>Petrodomas</i>	<i>sultan</i>	Elephant shrew	13.86

Table V. Serological taxonomy ordered by increasing spur size  
chicken anti chimpanzee serum

<i>Pan</i>	<i>troglodytes</i>	Chimpanzee	0.00
<i>Homo</i>	<i>sapiens</i>	Man	0.12
<i>Gorilla</i>	<i>gorilla</i>	Gorilla	0.14
<i>Pongo</i>	<i>pygmaeus</i>	Orangutan	0.67
<i>Symphalangus</i>	<i>syndactylus</i>	Siamang gibbon	0.85
<i>Hylobates</i>	<i>lar</i>	Gibbon	1.27
<i>Macaca</i>	<i>speciosa</i>	Stump-tail macaque	2.51
<i>Presbytis</i>	<i>entellus</i>	Langur	2.61
<i>Cebus</i>		Capuchin	4.55

Table VI. Serological taxonomy ordered by increasing spur size  
chicken anti gorilla serum

<i>Gorilla</i>	<i>gorilla</i>	Gorilla	0.00
<i>Homo</i>	<i>sapiens</i>	Man	0.11
<i>Pan</i>	<i>troglodytes</i>	Chimpanzee	0.25
<i>Pongo</i>	<i>pygmaeus</i>	Orangutan	0.77
<i>Symphalangus</i>	<i>syndactylus</i>	Siamang gibbon	0.80
<i>Hylobates</i>	<i>lar</i>	Gibbon	1.14

Table IV. (Continued)

<i>Macaca</i>	<i>irus</i>	Cynomologus monkey	1.65
<i>Macaca</i>	<i>speciosa</i>	Stump-tail macaque	1.65
<i>Presbytis</i>	<i>entellus</i>	Langur	1.65
<i>Cebus</i>		Capuchin	2.68

Table VII. Serological tyxonomy ordered by increasing spur size  
chicken anti orangutan serum

<i>Homo</i>	<i>sapiens</i>	Man	0.66
<i>Gorilla</i>	<i>gorilla</i>	Gorilla	0.84
<i>Pan</i>	<i>troglydotes</i>	Chimpanzee	0.85
<i>Symphalangus</i>	<i>syndactylus</i>	Siamang gibbon	0.93
<i>Hylobates</i>	<i>lar</i>	Gibbon	1.30
<i>Macaca</i>	<i>speciosa</i>	Stump-tail macaque	2.17
<i>Ateles</i>	<i>geoffroyi</i>	Spider monkey	2.70
<i>Presbytis</i>	<i>entellus</i>	Langur	3.39
<i>Lagothrix</i>	<i>lagothricha</i>	Woolly monkey	4.11
<i>Aotes</i>	<i>trivirgatus</i>	Night monkey	4.11
<i>Cebus</i>		Capuchin	4.47

Table VIII. Serological taxonomy ordered by increasing spur size  
chicken anti gibbon serum

<i>Hylobates</i>	<i>lar</i>	Gibbon	0.00
<i>Symphalangus</i>	<i>syndactylus</i>	Siamang gibbon	0.13
<i>Gorilla</i>	<i>gorilla</i>	Gorilla	0.73
<i>Pongo</i>	<i>pygmaeus</i>	Orangutan	0.83
<i>Homo</i>	<i>sapiens</i>	Man	0.95
<i>Pan</i>	<i>troglydotes</i>	Chimpanzee	0.98
<i>Pan</i>	<i>paniscus</i>	Pygmy chimpanzee	0.98



Table VIII. (Continued)

<i>Colobus</i>	<i>polykomos</i>	Colubus	2.58
<i>Macaca</i>	<i>mulatta</i>	Rhesus monkey	2.67
<i>Macaca</i>	<i>speciosa</i>	Stump-tail macaque	2.67
<i>Presbytis</i>	<i>entellus</i>	Langur	2.76
<i>Presbytis</i>	<i>cristatus</i>		2.76
<i>Cercopithecus</i>	<i>aethiops</i>	Vervet	3.11
<i>Ateles</i>	<i>geoffroyi</i>	Spider monkey	3.31
<i>Ateles</i>		Spider monkey	3.31
<i>Aotes</i>	<i>trivirgatus</i>	Night monkey	3.58
<i>Lagothrix</i>	<i>lagothricha</i>	Woolly monkey	3.98
<i>Lagothrix</i>		Woolly monkey	3.98
<i>Cebus</i>	<i>albifrons</i>	Capuchin	4.21
<i>Cebus</i>	<i>apella</i>	Capuchin	4.21
<i>Cebus</i>		Capuchin	4.21

Table IX. Taxonomic placement scores from rabbit anti human albumin results

			Increas- ing spur size <sup>1</sup>	MC'F data log ID <sup>2</sup>	Quantitative precipitation <sup>3</sup>
<i>Homo</i>	<i>sapiens</i>	Man	0.00000	0.00000	0.00
<i>Pan</i>	<i>trogodytes</i>	Chimpanzee	0.00000	0.05690	0.04
<i>Gorilla</i>	<i>gorilla</i>	Gorilla	0.00000	0.03743	0.02
<i>Hylobates</i>	<i>lar</i>	Gibbon	0.42565	0.10721	0.18
<i>Symphalangus</i>	<i>syndactylus</i>	Siamang gibbon	0.61907	0.11394	
<i>Pongo</i>	<i>pygmaeus</i>	Orangutan	1.09286	0.08636	
<i>Macaca</i>	<i>mulatta</i>	Rhesus monkey	3.26777	0.34830	0.18
<i>Macaca</i>	<i>speciosa</i>	Stump-tail macaque			
<i>Macaca</i>	<i>irus</i>	Cynomologus monkey			
<i>Macaca</i>	<i>nemestrina</i>	Pig-tail macaque			
<i>Cynopithecus</i>	<i>niger</i>	Black ape			
<i>Cercocebus</i>	<i>galeritus</i>	Mangabey	3.57755	0.36173	0.22

Table IX. (Continued)

			Increasing spur size <sup>1</sup>	MC <sup>2</sup> F data log ID <sup>2</sup>	Quantitative precipitation <sup>3</sup>
<i>Papio</i>	<i>papio</i>	Baboon	3.68330	0.38739	0.22
<i>Papio</i>	<i>hamadryas</i>	Baboon			
<i>Erythrocebus</i>	<i>patas</i>	Patas monkey	3.82754		0.24
<i>Cercopithecus</i>	<i>aethiops</i>	Vervet	3.83479	0.41330	0.24
<i>Colobus</i>	<i>polykomos</i>	Colubus	4.19873	0.40140	0.20
<i>Aotes</i>	<i>trivirgatus</i>	Night monkey	4.40002	0.42325	0.23
<i>Presbytis</i>	<i>entellus</i>	Langur	4.53925		
<i>Theropithecus</i>	<i>gelada</i>	Gelada baboon	4.76044		
<i>Chiropates</i>	<i>satanas</i>	Saki	6.17587		
<i>Cacajao</i>	<i>rubicundus</i>	Red-faced uakari	6.47585		
<i>Ateles</i>	<i>geoffroyi</i>	Spider monkey	6.57580	0.62325	0.35
<i>Ateles</i>		Spider monkey	6.57583		
<i>Callicebus</i>		Titi	6.57590	0.62325	
<i>Lagothrix</i>		Woolly monkey	6.70651		0.40
<i>Oedipomidas</i>	<i>oedipus</i>	Cotton-top marmoset	6.77589		
<i>Saguinus</i>	<i>fuscicollis</i>		6.77590		
<i>Saimiri</i>	<i>sciureus</i>	Squirrel monkey	6.92809	0.65321	0.38
<i>Saimiri</i>		Squirrel monkey	6.92814		
<i>Cebus</i>		Capuchin	7.44250	0.69897	0.48
<i>Urogale</i>	<i>everetti</i>	Tree shrew	7.91388		
<i>Galago</i>	<i>crassicaudatus</i>	Bush baby	9.08192	0.93450	0.69
<i>Galago</i>		Bush baby	9.08200		
<i>Nycticebus</i>	<i>coucang</i>	Slow loris	9.39190	1.04922	
<i>Tarsius</i>	<i>syrichta</i>	Tarsier	9.45446	1.05308	
<i>Tupaia</i>	<i>glis</i>	Tree shrew	9.95142	0.88081	0.64
<i>Perodicticus</i>	<i>potto</i>	Potto	10.19110		0.66
<i>Loris</i>	<i>tardigradus</i>	Slender loris	10.39472		

Table IX. (Continued)

			Increas- ing spur size <sup>1</sup>	MC'F data log ID <sup>2</sup>	Quantitative precipitation <sup>3</sup>
<i>Lemur</i>	<i>fulvus</i>	Lemur	10.65455	1.25527	0.62
<i>Lemur</i>	<i>fulvus fulvus</i>	Lemur	10.65458		
<i>Lemur</i>	<i>fulvus collaris</i>	Lemur	10.65458		
<i>Lemur</i>	<i>mongoz</i>	Lemur	10.65461		
<i>Atelerix</i>		African hedgehog	11.39486		
<i>Arctocebus</i>	<i>calabarensis</i>	Angwantibo	11.59475		
<i>Propithecus</i>	<i>verreauxi</i> <i>coquerele</i>	Indus	11.94953		0.77
<i>Erinaceus</i>	<i>europa</i>	European hedgehog	13.58065		0.84
<i>Potos</i>		Kinkajou	13.95354		
<i>Bos</i>	<i>taurus</i>	Bovine	14.08211	1.50515	
<i>Elephas</i>	<i>maximus</i>	Asiatic elephant	14.71041		
<i>Dasypus</i>	<i>novemcinctus</i>	Nine-banded armadillo	14.95140		
<i>Myrmecophaga</i>		Giant ant-eater	14.95141		
<i>Bradypus</i>		Three-toed sloth	14.95143		

1 Computer processing, with the grouping statement which treats the different species in each genus as a single group (see text), of the coded results obtained with six rabbit anti-human albumin sera yields the values listed in this column.

2 These values are calculated from the last column of table 3 in SARICH and WILSON [1966], which lists Index of Dissimilarity (ID) values obtained with three rabbit anti-human albumin sera mixed together in reciprocal proportion to their MC'F titers. Only the genus designations of the analyzed sera are considered in the listing of these scores.

3 The values listed are calculated from the percentage correspondences of the heterologous albumins to homologous (or human) albumin at 1.0 antigen equivalence shown in table 1 of HAFLEIGH and WILLIAMS [1966] from results obtained with two pools of rabbit anti-human albumin sera. The percentages are treated as fractions and subtracted from unity to give the values listed above. Only the genus designation of the analyzed sera are considered in the listing of these scores.

Table X. Taxonomic placement scores from rabbit anti human transferrin results

			increasing spur size <sup>1</sup>	radioimmune inhibition <sup>2</sup>
<i>Homo</i>	<i>sapiens</i>	Man	0.00000	0.00
<i>Pan</i>	<i>troglodytes</i>	Chimpanzee	0.00000	0.00
<i>Gorilla</i>	<i>gorilla</i>	Gorilla	0.11097	0.00
<i>Pongo</i>	<i>pygmaeus</i>	Orangutan	1.46281	0.10
<i>Symphalangus</i>	<i>syndactylus</i>	Siamang gibbon	1.83498	0.10
<i>Hylobates</i>	<i>lar</i>	Gibbon	1.87760	0.10
<i>Hylobates</i>		Gibbon		
<i>Erythrocebus</i>	<i>patas</i>	Patas monkey	3.11217	0.29
<i>Macaca</i>	<i>mulatta</i>	Rhesus monkey	3.75731	0.31
<i>Macaca</i>	<i>speciosa</i>	Stump-tail macaque		
<i>Macaca</i>	<i>nemestrina</i>	Pig-tail macaque		
<i>Cynopithecus</i>	<i>niger</i>	Black ape		
<i>Cercocebus</i>	<i>galeritus</i>	Mangabey	3.86217	0.27
<i>Cercopithecus</i>	<i>aethiops</i>	Vervet	3.86217	0.49
<i>Presbytis</i>	<i>entellus</i>	Langur	4.11216	
<i>Colobus</i>	<i>polykomas</i>	Colubus	4.61215	
<i>Papio</i>	<i>hamadryas</i>	Baboon	4.86215	0.31
<i>Theropithecus</i>	<i>gelada</i>	Gelada baboon	4.86217	
<i>Saimiri</i>	<i>sciureus</i>	Squirrel monkey	5.05641	0.60
<i>Saimiri</i>		Squirrel monkey	5.05644	
<i>Saguinus</i>	<i>fuscicollis</i>		5.63055	0.74
<i>Cacajao</i>	<i>rubicundus</i>	Red-faced uakari	5.88053	
<i>Lagothrix</i>		Woolly monkey	6.13051	0.69
<i>Aotes</i>	<i>trivirgatus</i>	Night or owl monkey	6.16706	0.71
<i>Cebus</i>		Capuchin	6.38049	0.54
<i>Chiropates</i>	<i>satanas</i>	Saki	6.63050	
<i>Callicebus</i>		Titi	6.63051	0.78
<i>Ateles</i>		Spider monkey	6.88049	



Table X. (Continued)

			increasing spur size <sup>1</sup>	radioimmune inhibition <sup>2</sup>
<i>Loris</i>	<i>tardigradus</i>	Slender loris	10.02436	
<i>Lemur</i>	<i>fulvus fulvus</i>	Lemur	10.22435	0.89
<i>Lemur</i>	<i>fulvus</i>	Lemur	10.22436	
<i>Lemur</i>	<i>mongoz</i>	Lemur	10.22436	
<i>Nycticebus</i>	<i>coucang</i>	Slow loris	10.45981	0.89
<i>Arctocebus</i>	<i>calabarensis</i>	Angwantibo	10.62437	
<i>Perodicticus</i>	<i>potto</i>	Potto	10.62437	
<i>Atelerix</i>		African hedgehog	10.62437	
<i>Propithecus</i>	<i>verreauxi</i> <i>coquerele</i>	Indus	10.93023	
<i>Erinaceus</i>	<i>europa</i>	European hedgehog	10.93024	
<i>Tupaia</i>	<i>glis</i>	Tree shrew	10.93025	
<i>Galago</i>	<i>crassicaudatus</i>	Bush baby	10.95105	0.96
<i>Galago</i>		Bush baby	10.95109	
<i>Bos</i>	<i>taurus</i>	Bovine	10.95117	
<i>Potos</i>		Kinkajou	11.10658	

1 Computer processing with the generic grouping statement of the coded results obtained with five rabbit anti-human transferrin sera yields the values listed in this column.

2 The values listed are calculated from the percentage cross reactivities of the heterologous transferrins to homologous (or human) transferrin shown in table 1 of WANG *et al.* [1968]. The percentages are treated as fractions and subtracted from unity to give the values listed above. Only the genus designations of the analyzed sera are considered in the listing of these scores.

Table XI. Serological taxonomy ordered by increasing spur size  
rabbit anti human alpha 2 macroglobulin

<i>Homo</i>	<i>sapiens</i>	Man	0.00
<i>Gorilla</i>	<i>gorilla</i>	Gorilla	0.00
<i>Pan</i>	<i>troglydytes</i>	Chimpanzee	0.36

Table XI. (Continued)

<i>Colobus</i>	<i>polykomas</i>	Colubus	0.71
<i>Pongo</i>	<i>pygmaeus</i>	Orangutan	0.81
<i>Presbytis</i>	<i>entellus</i>	Langur	1.22
<i>Hylobates</i>		Gibbon	1.43
<i>Hylobates</i>	<i>lar</i>	Gibbon	1.43
<i>Cercocebus</i>	<i>galeritus</i>	Mangabey	1.63
<i>Macaca</i>	<i>speciosa</i>	Stump-tail macaque	1.71
<i>Macaca</i>	<i>nemestrina</i>	Pig-tail macaque	1.71
<i>Macaca</i>	<i>mulatta</i>	Rhesus monkey	1.71
<i>Macaca</i>	<i>maura</i>	Moor macaque	1.71
<i>Macaca</i>	<i>cyclopis</i>	Formosan macaque	1.71
<i>Cercopithecus</i>	<i>aethiops</i>	Vervet	1.90
<i>Theropithecus</i>	<i>gelada</i>	Gelada baboon	1.90
<i>Symphalangus</i>	<i>syndactylus</i>	Siamang gibbon	2.08
<i>Papio</i>	<i>anubis</i>	Baboon	2.16
<i>Papio</i>	<i>hamadryas</i>	Baboon	2.16
<i>Saimiri</i>		Squirrel monkey	4.64
<i>Saimiri</i>	<i>sciurea</i>	Squirrel monkey	4.64
<i>Aotes</i>	<i>trivirgatus</i>	Night monkey	4.65
<i>Lagothrix</i>		Woolly monkey	4.78
<i>Cebus</i>		Capuchin	4.78
<i>Ateles</i>		Spider monkey	5.70
<i>Lemur</i>	<i>fulvus fulvus</i>	Lemur	5.75
<i>Lemur</i>	<i>mongoz</i>	Lemur	5.75
<i>Lemur</i>	<i>fulvus</i>	Lemur	5.75
<i>Rangifer</i>	<i>caribou</i>	Reindeer	7.23
<i>Tapirus</i>	<i>terrestris</i>	Tapir	7.23
<i>Bos</i>	<i>taurus</i>	Bovine	7.67
<i>Delphinopterus</i>	<i>leucas</i>	White whale	7.67
<i>Loris</i>	<i>tardigradus</i>	Slender loris	7.73
<i>Equus</i>	<i>equus</i>	Horse	7.74
<i>Nycticebus</i>	<i>coucang</i>	Slow loris	8.29
<i>Galago</i>		Bush baby	8.34

Table XI. (Continued)

<i>Galago</i>	<i>senegalensis</i>	Bush baby	8.34
<i>Galago</i>	<i>crassicaudatus</i>	Bush baby	8.34
<i>Felis</i>	<i>temminckii</i>	Golden cat	8.41
<i>Petrodomas</i>	<i>sultan</i>	Elephant shrew	8.43
<i>Perodicticus</i>	<i>potto</i>	Potto	8.45
<i>Dasypus</i>	<i>novemcinctus</i>	Nine-banded armadillo	8.60
<i>Zalophus</i>	<i>californianus</i>	California sea lion	9.09
<i>Marmota</i>	<i>monax</i>	Woodchuck	9.09
<i>Tupaia</i>	<i>glis</i>	Tree shrew	9.09
<i>Rhynchocyon</i>		Elephant shrew	9.36
<i>Canis</i>	<i>familiaris</i>	Dog	9.36
<i>Elephas</i>	<i>maximus</i>	Asiatic elephant	10.15
<i>Manis</i>	<i>pentodactyla</i>	Pangolin	10.52
<i>Erinaceus</i>	<i>europa</i>	European hedgehog	10.64
<i>Rattus</i>		Rat	11.22
<i>Cavia</i>		Guinea pig	13.90
<i>Macropus</i>	<i>rufus</i>	Red kangaroo	14.65

Table XII. Serological taxonomy ordered by increasing spur size  
rabbit anti human thyroglobulin

<i>Homo</i>	<i>sapiens</i>	Man	0.00
<i>Pan</i>	<i>troglodytes</i>	Chimpanzee	1.72
<i>Gorilla</i>	<i>gorilla</i>	Gorilla	1.79
<i>Pongo</i>	<i>pygmaeus</i>	Orangutan	1.99
<i>Hylobates</i>	<i>lar</i>	Gibbon	3.20
<i>Macaca</i>	<i>irus</i>	Cynomologus monkey	4.00
<i>Theropithecus</i>	<i>gelada</i>	Gelada baboon	4.43
<i>Papio</i>		Baboon	4.61
<i>Colobus</i>	<i>polykomos</i>	Colubus	5.10

Table XII. (Continued)

<i>Saimiri</i>		Squirrel monkey	5.29
<i>Bos</i>	<i>taurus</i>	Bovine	9.17
<i>Perodicticus</i>	<i>potto</i>	Potto	9.73

Table XIII. Serological taxonomy ordered by increasing spur size  
rabbit anti human gamma globulin

<i>Homo</i>	<i>sapiens</i>	Man	0.00
<i>Pan</i>	<i>troglodytes</i>	Chimpanzee	0.22
<i>Gorilla</i>	<i>gorilla</i>	Gorilla	0.65
<i>Pongo</i>	<i>pygmaeus</i>	Orangutan	1.35
<i>Cercocebus</i>	<i>galeritus</i>	Mangabey	2.88
<i>Symphalangus</i>	<i>syndactylus</i>	Siamang gibbon	3.04
<i>Theropithecus</i>	<i>gelada</i>	Gelada baboon	3.13
<i>Erythrocebus</i>	<i>patas</i>	Patas monkey	3.21
<i>Cercopithecus</i>	<i>aethiops</i>	Vervet	3.21
<i>Papio</i>	<i>hamadryas</i>	Baboon	3.21
<i>Macaca</i>	<i>mulatta</i>	Rhesus monkey	3.49
<i>Macaca</i>	<i>nemestrina</i>	Pig-tail macaque	3.49
<i>Cynopithecus</i>	<i>niger</i>	Black ape	3.49
<i>Macaca</i>	<i>speciosa</i>	Stump-tail macque	3.49
<i>Hylobates</i>	<i>lar</i>	Gibbon	3.36
<i>Hylobates</i>		Gibbon	3.36
<i>Colobus</i>	<i>polykomos</i>	Colubus	3.88
<i>Presbytis</i>	<i>entellus</i>	Langur	4.63
<i>Ateles</i>	<i>fusciceps</i>	Spider monkey	5.39
<i>Ateles</i>	<i>Geoffroyi</i>	Spider monkey	5.39
<i>Saimiri</i>		Squirrel monkey	5.55
<i>Saimiri</i>	<i>sciureus</i>	Squirrel monkey	5.55
<i>Aotes</i>	<i>trivirgatus</i>	Night monkey	5.95
<i>Propithecus</i>	<i>verreauxi coquerele</i>	Indus	6.98
<i>Lemur</i>		Lemur	8.39



Table XIII. (Continued)

<i>Lemur</i>	<i>fulvus fulvus</i>	Lemur	8.39
<i>Lemur</i>	<i>fulvus</i>	Lemur	8.39
<i>Galago</i>	<i>crassicaudatus</i>	Bush baby	8.74
<i>Galago</i>		Bush baby	8.74
<i>Galago</i>	<i>senegalensis</i>	Bush baby	8.74
<i>Nycticebus</i>	<i>coucang</i>	Slow loris	9.22
<i>Bos</i>	<i>taurus</i>	Bovine	10.39
<i>Petrodomas</i>	<i>sultan</i>	Elephant shrew	11.93
<i>Tupaia</i>	<i>glis</i>	Tree shrew	11.93
<i>Urogale</i>	<i>everetti</i>	Tree shrew	12.58
<i>Erinacus</i>	<i>europa</i>	European hedgehog	13.30

Table XIV. Serological taxonomy ordered by increasing spur size  
rabbit anti human ceruloplasmin

<i>Homo</i>	<i>sapiens</i>	Man	0.00
<i>Pan</i>	<i>trogodytes</i>	Chimpanzee	0.00
<i>Gorilla</i>	<i>gorilla</i>	Gorilla	0.00
<i>Hylobates</i>	<i>lar</i>	Gibbon	1.67
<i>Pongo</i>	<i>pygmaeus</i>	Orangutan	2.00
<i>Macaca</i>	<i>speciosa</i>	Stump-tail macaque	2.33
<i>Presbytis</i>	<i>entellus</i>	Langur	2.58
<i>Saimiri</i>		Squirrel monkey	5.82
<i>Aotes</i>	<i>trivirgatus</i>	Night monkey	6.09
<i>Propithecus</i>	<i>verreauxi coquerele</i>	Indus	7.76
<i>Lemur</i>	<i>fulvus fulvus</i>	Lemur	9.13
<i>Galago</i>	<i>crassicaudatus</i>	Bush baby	9.44
<i>Nycticebus</i>	<i>coucang</i>	Slow loris	9.85
<i>Tupaia</i>	<i>glis</i>	Tree shrew	11.01
<i>Petrodomas</i>	<i>sultan</i>	Elephant shrew	11.01
<i>Erinaceus</i>	<i>europa</i>	European hedgehog	12.51

Table XV. Serological taxonomy of primates ordered by increasing spur size rabbit anti chimpanzee serum

<i>Pan</i>	<i>troglodytes</i>	Chimpanzee	0.00
<i>Pan</i>	<i>paniscus</i>	Pygmy chimpanzee	0.00
<i>Gorilla</i>	<i>gorilla</i>	Gorilla	0.00
<i>Homo</i>	<i>sapiens</i>	Man	0.05
<i>Pongo</i>	<i>pygmaeus</i>	Orangutan	0.53
<i>Symphalangus</i>	<i>syndacatylus</i>	Siamang gibbon	1.67
<i>Hylobates</i>	<i>lar</i>	gibbon	1.88
<i>Cercopithecus</i>	<i>aethiops</i>	Vervet	2.58

Table XVI. Serological taxonomy ordered by increasing spur size rabbit anti chimpanzee thyroglobulin

<i>Pan</i>	<i>troglodytes</i>	Chimpanzee	0.00
<i>Gorilla</i>	<i>gorilla</i>	Gorilla	0.28
<i>Homo</i>	<i>sapiens</i>	Man	0.45
<i>Pongo</i>	<i>pygmaeus</i>	Orangutan	0.70
<i>Hylobates</i>	<i>lar</i>	Gibbon	1.71
<i>Colobus</i>	<i>polykomos</i>	Colubus	2.67
<i>Theropithecus</i>	<i>gelada</i>	Gelada baboon	2.73
<i>Macaca</i>	<i>irus</i>	Cynomologus monkey	3.10
<i>Papio</i>		Baboon	3.65
<i>Saimiri</i>		Squirrel monkey	5.92

Table XVII. Serological taxonomy ordered by increasing spur size rabbit anti gibbon serum

<i>Hylobates</i>	<i>lar</i>	Gibbon	0.00
<i>Hylobates</i>	<i>pileatus</i>	Gibbon	0.00

Table XVII. (Continued)

<i>Symphalangus</i>	<i>syndactylus</i>	Siamang gibbon	0.23
<i>Homo</i>	<i>sapiens</i>	Man	1.50
<i>Gorilla</i>	<i>gorilla</i>	Gorilla	1.61
<i>Pongo</i>	<i>pygmaeus</i>	Orangutan	1.68
<i>Pan</i>	<i>troglodytes</i>	Chimpanzee	1.88
<i>Pan</i>	<i>paniscus</i>	Pygmy chimpanzee	1.88
<i>Cercopithecus</i>	<i>aethiops</i>	Vervet	2.15
<i>Presbytis</i>	<i>entellus</i>	Langur	2.16
<i>Colobus</i>	<i>polykomos</i>	Colubus	2.37
<i>Theropithecus</i>	<i>gelada</i>	Gelada baboon	2.57
<i>Cercocebus</i>	<i>torquatus</i>	Mangabey	2.57
<i>Erythrocebus</i>	<i>patas</i>	Patas monkey	2.57
<i>Macaca</i>	<i>mulatta</i>	Rhesus monkey	2.57
<i>Macaca</i>	<i>nemestrina</i>	Pig-tail macaque	2.57
<i>Nasalis</i>	<i>larvatus</i>	Proboscis monkey	2.88
<i>Aotes</i>	<i>trivirgatus</i>	Night monkey	4.23
<i>Saimiri</i>	<i>sciureus</i>	Squirrel monkey	4.86
<i>Lemur</i>	<i>fulvus</i>	Lemur	8.32
<i>Tupaia</i>	<i>glis</i>	Tree shrew	8.51
<i>Galago</i>	<i>crassicaudatus</i>	Bush baby	8.71
<i>Nycticebus</i>	<i>coucang</i>	Slow loris	8.71
<i>Loris</i>	<i>tardigradus</i>	Slender loris	8.80
<i>Bradypus</i>		Three-toed sloth	9.28
<i>Perodicticus</i>	<i>potto</i>	Potto	9.38
<i>Dasypus</i>	<i>novemcinctus</i>	Nine-banded armadillo	9.48
<i>Bos</i>	<i>taurus</i>	Bovine	9.67
<i>Myrmecophaga</i>		Giant ant-eater	9.67
<i>Loxodonta</i>	<i>africana</i>	African elephant	9.76
<i>Potos</i>		Kinkajou	10.05
<i>Citellus</i>	<i>mexicanus</i>	Ground squirrel	10.73

Table XVII. (Continued)

<i>Atelerix</i>		African hedgehog	10.95
<i>Nasilio</i>	<i>brachyrhynchus</i> <i>brachyrhynchus</i>	Elephant shrew	11.50
<i>Tenrec</i>	<i>ecaudatus</i>	Tenrec	11.88
<i>Didelphis</i>	<i>virginianus</i>	Opossum	11.88
<i>Suncus</i>	<i>murinustybr</i>	Garden shrew	11.98

Table XVIII. Serological taxonomy of primates ordered by increasing spur size  
cebus anti human serum

<i>Homo</i>	<i>sapiens</i>	Man	0.00
<i>Gorilla</i>	<i>gorilla</i>	Gorilla	0.71
<i>Pan</i>	<i>troglodytes</i>	Chimpanzee	0.99
<i>Pongo</i>	<i>pygmaeus</i>	Orangutan	2.14
<i>Hylobates</i>	<i>lar</i>	Gibbon	2.41
<i>Macaca</i>	<i>mulatta</i>	Rhesus monkey	3.17
<i>Saimiri</i>		Squirrel monkey	8.05
<i>Aotes</i>	<i>trivirgatus</i>	Night monkey	8.05

Table XIX. Serological taxonomy of primates ordered by increasing spur size  
woolly anti chimpanzee serum

<i>Pan</i>	<i>troglodytes</i>	Chimpanzee	0.00
<i>Pan</i>	<i>paniscus</i>	Pygmy chimpanzee	0.38
<i>Homo</i>	<i>sapiens</i>	Man	0.60
<i>Gorilla</i>	<i>gorilla</i>	Gorilla	0.64
<i>Pongo</i>	<i>pygmaeus</i>	Orangutan	2.34
<i>Hylobates</i>	<i>lar</i>	Gibbon	2.95
<i>Symphalangus</i>	<i>syndactylus</i>	Siamang gibbon	3.26
<i>Macaca</i>	<i>irus</i>	Cynomologus monkey	4.63



Table XIX. (Continued)

<i>Cercocebus</i>	<i>aethiops</i>	Vervet	4.63
<i>Papio</i>	<i>anubis</i>	Baboon	4.63

Table XX. Serological taxonomy of primates ordered by increasing spur size spider anti chimpanzee serum

<i>Pan</i>	<i>troglodytes</i>	Chimpanzee	0.00
<i>Pan</i>	<i>paniscus</i>	Pygmy chimpanzee	0.00
<i>Homo</i>	<i>sapiens</i>	Man	0.64
<i>Gorilla</i>	<i>gorilla</i>	Gorilla	0.94
<i>Pongo</i>	<i>pygmaeus</i>	Orangutan	2.37
<i>Hylobates</i>	<i>lar</i>	Gibbon	2.49
<i>Symphalangus</i>	<i>syndactylus</i>	Siamang gibbon	2.60
<i>Macaca</i>	<i>speciosa</i>	Stump-tail macaque	4.40
<i>Presbytis</i>	<i>entellus</i>	Langur	4.40
<i>Cercopithecus</i>	<i>aethiops</i>	Vervet	5.59
<i>Papio</i>	<i>anubis</i>	Baboon	5.59
<i>Macaca</i>	<i>irus</i>	Cynomologus monkey	5.59

Table XXI. Serological taxonomy ordered by increasing spur size vervet anti human serum

<i>Homo</i>	<i>sapiens</i>	Man	0.00
<i>Pan</i>	<i>troglodytes</i>	Chimpanzee	1.14
<i>Gorilla</i>	<i>gorilla</i>	Gorilla	1.61
<i>Pongo</i>	<i>pygmaeus</i>	Orangutan	3.44
<i>Symphalangus</i>	<i>syndactylus</i>	Siamang gibbon	3.92
<i>Hylobates</i>	<i>lar</i>	Gibbon	3.96

Table XXII. Serological taxonomy of primates ordered by increasing spur size  
vervet anti chimpanzee serum

<i>Pan</i>	<i>troglodytes</i>	Chimpanzee	0.00
<i>Pan</i>	<i>paniscus</i>	Pygmy chimpanzee	0.00
<i>Homo</i>	<i>sapiens</i>	Man	0.79
<i>Gorilla</i>	<i>gorilla</i>	Gorilla	1.07
<i>Pongo</i>	<i>pygmaeus</i>	Orangutan	2.58
<i>Hylobates</i>	<i>lar</i>	Gibbon	2.91
<i>Hylobates</i>	<i>pileatus</i>	Gibbon	2.91

Table XXIII. Time scale of hominoid branching in millions of years,  
estimated from spur size placement tables

Branching between	Chickens	Antisera produced in		Cercopithecoids
		Rabbits	Ceboids	
P-H	2.4			5.1
P-G		1.4	4.9	
G-P, H	3.3			7.1
H-P, G		3.5	6.2	
Po-H, P, G	12.1	10.3	16.4	16.4
Hy, S-Po, H, P, G	13.7	20.6	20.6	18.3 <sup>2</sup>
Hy, S, Po, H, P, G-Ce	30.0 <sup>1</sup>	30.0 <sup>1</sup>	30.0 <sup>1</sup>	

P = *Pan*, H = *Homo*, G = *Gorilla*, Po = *Pongo*, Hy = *Hylobates*, S = *Symphalangus*,  
Ce = Cercopithecoidea

1 The average spur size distance between hominoids and cercopithecoids is assumed to correspond to 30 million years and all the spur size distances between hominoids are represented in terms of this value.

2 18.3 million years is the mean values calculated from the Hy, S-Po, H, P, G branching values of the chicken, rabbit, and ceboid antisera results. All other values in this column are represented in terms of this value.

Table XXIV. DNA divergence from man

Animal DNA	Percent relatedness 68° C <sup>1</sup> Unfractionated			Time scale <sup>2</sup> in millions of years Unfractionated		
	DNA	AT-Rich	GC-Rich	DNA	AT-Rich	GC-Rich
Rhesus monkey	66	53	74	30	30	30
Gibbon	76	69	85	21	20	17
Chimpanzee	91	85	95	8	10	6

1 Taken from table 4 of MARTIN and HOYER [1967].

2 The percent relatedness between human and rhesus monkey DNA is assumed to correspond to 30 million years, and the percent relatedness between human and gibbon DNA and between human and chimpanzee DNA are represented in terms of this value.

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Authors' addresses: Dr. MORRIS GOODMAN, Plymouth State Home and Training School, Northville, MI 48167 and Wayne State University, School of Medicine, 1400 Chrysler Expressway, Detroit, MI 48207; Mr. G. WILLIAM MOORE, North Carolina State University, Institute of Statics, Biomathematics Program, Box 5457 College Station, Raleigh, NC 27607; Mr. WALTER FARRIS and Mrs. EMILY POULIK, Department of Anatomy, Wayne State University, School of Medicine, 1400 Chrysler Expressway, Detroit, MI 48207(USA).

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## CHIMPANZEE VIRUSES

S. S. KALTER and N. B. GUILLOUD

Division of Microbiology and Infectious Diseases  
Southwest Foundation for Research and Education  
San Antonio, TX  
Yerkes Regional Primate Center, Atlanta, GA

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### INTRODUCTION

Nonhuman primates are now employed extensively in many laboratories as the animal of choice for biomedical research. The primates utilized encompass several species of prosimians and a vast number of simians. Whereas the macaques and perhaps the squirrel monkeys enjoy the dubious position of those simians most widely used in the research laboratory, the chimpanzee is considered by the majority of investigators as that experimental animal most closely related to man and, therefore, most desirable for laboratory investigations. Although cost and general availability limit this animal's usefulness, several sizable colonies nonetheless do exist. Furthermore, an extensive number of fundamental experiments in various biomedical areas have been conducted using the chimpanzee as the experimental animal [1]. It would appear, therefore, that continued use of chimpanzees in biomedical research may be helped if investigators are provided certain information that may assist them in the evaluation of their experimental data. Undoubtedly infectious processes

strongly influence the general health and well-being of any animal colony, as well as final interpretation of the experimental data. This chapter presents current information relative to the status of the chimpanzee and its use in virus research.

#### HISTORICAL RÉSUMÉ

The successful demonstration by ENDERS and his collaborators of the use of primate tissues for the *in vitro* cultivation of viruses [2, 3] was shortly followed by the recognition that various tissues, body fluids and excreta of these animals also contained either adventitious agents or numerous viruses of one or another type [4–7]. A number of investigators quickly confirmed and extended these findings to include various species monkeys used in the laboratory: *Macaca mulatta*, *M. irus*, *Cercopithecus aethiops*, *Papio* sp. [8–12]. Recovery of viruses from other nonhuman primates (*Saguinus* sp., *Pan* sp.) has also been reported [13–19]. It is now quite apparent that occurrence of a *viral flora* in simians is not an isolated finding but commonplace and frequent. Undoubtedly additional viruses have been recovered from natural infections or tissues of other nonhuman primates but no attempt is made at this time to review the extensive literature in this regard. For a complete listing of currently recognized simian viruses and their host sources see KALTER and HEBERLING [20].

While attempts to recover viruses from chimpanzees may be relatively recent, use of this animal in experimental virology has a longer history. For example, yellow fever infections of chimpanzees was discussed by THOMAS in 1907 [21], HINDLE in 1929 [22] discussed viruses in regard to chimpanzees and human disease, and NICOLAU *et al.* [23] studied pseudorabies (Aujeszky's disease) in chimpanzees in 1938. Attempts to reproduce and simulate poliovirus infections of man in a laboratory animal led HOWE and BODIAN in 1940 to use the chimpanzee [24]. It may be recalled that monkeys had been used previously for the isolation of this virus by LANDSTEINER and POPPER [25]. Paralytic disease of zoo chimpanzees, diagnosed on the basis of clinical findings, was reported by a number of investigators [26–28]. A series of studies by HOWE and BODIAN, as well as others [29–36], have demonstrated the successful simulation of the human disease in chimpanzees by various picornaviruses including the polio-, coxsackie- and echoviruses. The role played by chimpanzees in the dissemination of hepatitis virus also has been well documented since HILLIS described an outbreak among handlers of these primates [37]. Other viruses that have been isolated from chimpanzees either as a result

of experimental infection or from normal animals include varicella, measles (rubeola), respiratory syncytial (chimpanzee coryza agent – CCA), cytomegalovirus, poxvirus, adenoviruses, reoviruses, foamy viruses, as well as several new suggested virus prototypes.

More recently, a number of studies have been generated that have contributed to our basic knowledge of the viral flora of the chimpanzee. One such study conducted in this laboratory surveys primate sera for antibodies to human and simian viruses [38]. This survey, in comparing sera obtained from various primates demonstrates an antibody profile on each primate species investigated with regard to its previous antigenic contacts. The study by SOIKE *et al.* [17] describes viruses recovered from the respiratory and alimentary tracts of normal chimpanzees. RODGERS and her coworkers [39] described the recovery of a number of viruses from chimpanzee tissue explants maintained in culture for long periods of time.

For purposes of orientation the information on viruses of chimpanzees as discussed herein has been divided into two major segments: 1. virus infections of 'normal' chimpanzees, and 2. viruses isolated from experimentally infected chimpanzees.

#### VIRUS INFECTIONS OF 'NORMAL' CHIMPANZEES

Surprisingly little information is available, nor have there been many extensive studies, on what may be considered as the virus flora of normal chimpanzees. The large number of recognized simian viruses that are counterparts of human viruses or representative of simians emphasizes the existence of a multiplicity of simian viruses. A certain number of the viruses are conceivably characteristic of chimpanzees. It is suggested that the large number of simian viruses now recognized and originally isolated from the monkey rather than from such higher apes as the chimpanzee may reflect the vast amount of work performed previously on numerous monkeys rather than on the more limited number of available chimpanzees. Certain of the early investigations employing chimpanzees, while not specifically studying the viral flora, did indicate the presence of viruses in these animals. For example, VOGEL and PINKERTON in 1955 [40] reported salivary gland virus (cytomegalovirus) occurring spontaneously in chimpanzees. Three chimpanzees, two 4 and one 17 years old, were found to have characteristic cellular lesions in various tissues of their bodies although virus isolations were not done. MORRIS and his coinvestigators [13], while studying an outbreak of respiratory disease occurring in a colony of 'normal'



chimpanzees recovered an agent from throat material of a chimpanzee with clinical coryza. This agent originally referred to as the chimpanzee coryza agent (CCA) was found by CHANOCK *et al.* [41, 42] to be identical with an agent recovered from infants with respiratory disease. The name CCA, which indicates a chimpanzee source, was changed shortly thereafter upon realization that this agent was of human origin [42]. Respiratory syncytial (RS) virus was suggested as a descriptive term based on the type of cytopathology produced in cell culture [42]. Varicella was reported as occurring among chimpanzees as well as other higher apes by HEUSCHELE [43]. DOUGLAS *et al.* [44] reported on the occurrence of molluscum contagiosum virus in chimpanzees and poxvirus ('chimpanzee pox') was reported by RAGHAVEN and KHAN [45]. These, however, must be considered as natural infections of the animals resulting from an outside (human?) source rather than as indigenous viruses. The possibility does exist that these viruses may occur as natural infections and animal to animal transmission cannot be excluded.

In this regard the studies of HARRISON *et al.* [46] are of interest as they demonstrated the presence of antibody to Chikungunya and several related viruses in sera of chimpanzees and other nonhuman primates. In this study serum neutralizing (SN) antibody to Chikungunya, Semliki Forest (Kumba strain), O'nyong-Nyong (MP 87 strain) and Mayaro (B strain) viruses was found to be present in wild-born chimpanzees. Furthermore, SN antibody was also found to Chikungunya, O'nyong-Nyong, and Mayaro viruses in chimpanzees born in the United States. This raises the question regarding the origin of these antibodies. The most feasible explanation resides in an anamnestic response as a result of infection with antigenically related organisms. In support of this conclusion is the finding by KALTER *et al.* [38] of antibody to Western encephalitis virus, also a Group A arbovirus, in this same colony of chimpanzees described by HARRISON *et al.* [46]. Therefore, the possibility of these antibodies resulting from direct infection of the domestic animals with such exotic agents as Chikungunya and related viruses must indeed be considered as remote at this time.

Because of the extensive employment of nonhuman primates in biomedical research, a program has been developed by KALTER and his coinvestigators to establish a microbiologic profile on various available simians primarily as maintained in captivity. While the main effort has centered around the baboon (*Papio* sp.) as existing in nature as well as in captivity, comparative data have been accumulated on the chimpanzee. A recent report [38] presents data on chimpanzee sera obtained from a number of different primate facilities and examined for antibodies to viruses of human and simian origin (tables I-VII).

Two major conclusions may be drawn from these data: 1. antibodies were consistently present, albeit to varying degrees, to different members of human and nonhuman picornaviruses, reoviruses, myxoviruses, adenoviruses, arboviruses, and to a number of miscellaneous viruses, and 2. marked variation in incidence of antibody was observed in the chimpanzees maintained at the different participating facilities. A third, and perhaps the most important consideration, concerns the fact that, as will be described below, a large number of human viruses, i.e. viruses capable of causing infection and/or disease of man, have been found in association with the chimpanzee.

It is highly conceivable that these diversified antibodies result from contact with virus infected humans or other primates. In interpreting any serologic response, anamnestic reactions always must be taken into consideration. In a few instances vaccination may have been responsible for eliciting the antibody response. This is probably true in a certain number of chimpanzees with poliovirus antibody although an epidemic of poliomyelitis had previously occurred in that colony [47]. Other interesting observations with regard to antibody findings may be summarized as follows:

*Picornaviruses* (table I). A number of comments additional to those noted above may be made regarding poliovirus infections of the chimpanzee. For example, the data suggest that this same facility that experienced a poliovirus outbreak also had an 'epidemic' due to coxsackievirus A 20 in the period between the 1966 and 1967 bleedings. Approximately 59.4% (38/64) animals serologically converted from negative to positive during this interval. Other seroconversions were found to occur at this same facility to a number of other picornaviruses: echovirus type 3 - 12.5% (1963), 71.1% (1966), and 44.6% (1967); echovirus type 7 - 0.0% (1963), 23.3% (1966), and 41.6% (1967); echovirus type 11 - 12.5% (1963), 26.3% (1966), and 35.4% (1967); and to a lesser degree to echoviruses types 12 and 13. Very little or no evidence of chimpanzee infection was demonstrated for two simian enteroviruses, SV 16 and SV 45. Inasmuch as these two viruses were originally recovered from Asian animals (*M. mulatta*, *M. irus*), this finding is not too surprising although, as will be pointed out below, this rule is not always applicable, especially as it concerns animals held for long periods in captivity and in contact with other primates. The serologic findings on chimpanzees from other facilities substantiate this general lack of infectivity with these two simian enteroviruses. It might be stated that studies on chimpanzees in the other colonies correlated quite well with those described. Previous studies reported from this laboratory had shown a somewhat higher incidence of antibody to other simian picornaviruses, i.e.

Table I. Serological results with representative picornaviruses

Virus	Type of Test	S.F.R.E. <sup>2</sup>				Lab #1		Lab Born		Lab #2	Lab #4	Lab #7
		Pre	1	2	3	4	1963	1966	1967	1967	1967	1967
Polio	1	SN <sup>1</sup>	4/18 <sup>3</sup>				4/52		14/25	1/24	0/11	1/25
	2	SN	3/19				16/52		10/25	7/21	3/11	23/25
	3	SN	3/18				9/25		13/25	5/24	4/11	0/20
Coxs. A9	SN		4/18				7/52		6/22	4/23	1/9	
	A20	HI	0/17	0/17	0/17	0/16	4/15	0/16	0/38	0/29	38/64	0/23
	B1	SN	0/18				0/52		0/22	1/24	0/11	
	B2	SN	0/18				3/52		1/21	1/24	1/11	
	B3	SN	0/18				0/52		1/21	0/22	1/10	
	B4	SN	1/17				0/52		0/19	0/19	0/9	
	B5	SN	0/17				2/52		0/20	1/19	0/9	
	B6	SN	1/17				3/50		0/21	0/15	0/9	
Echo	1	SN	0/17				1/51		0/21	1/24	2/11	
	3	HI	11/17	6/17	12/17	2/16	7/16	2/16	27/38	12/19	29/65	3/23
	6	SN	4/18				10/20		6/25	1/4		12/25
	7	HI	13/17	9/16	12/17	9/15	10/16	0/25	7/30	25/27	27/65	17/23
	9	SN	2/18				3/35		1/22	0/9		0/25
	11	HI	11/17	5/17	3/17	0/6	1/15	2/16	9/38	3/29	23/65	3/23
	12	HI	3/17	3/16	3/17	0/15	1/16	12/56	8/41	22/27	13/65	1/23
	13	HI	1/17	1/17	1/17	2/16	3/15	0/16	4/38	1/29	10/65	0/23
A	13	SN					0/52			8/18	1/11	
	SV 4	SN					0/51			0/23	2/11	
	SV 16	HI	3/17	1/16	3/17	2/16	2/15	0/13	0/24	1/26	0/62	1/23
	SV 19	SN					8/51					8/22
	SV 45	HI	0/17	0/18	0/18	0/16	0/18	3/28	0/38	0/27	0/69	0/21
	SV 49	SN					9/52					2/24

1 SN = serum neutralization; HI = hemagglutination inhibition.

2 Samples taken approximately 1-2 months apart. 'Pre' indicates serum collected at time of capture.

3 Numerator = number of positive sera; denominator = number of sera tested.

type SV 19 and SV 49, also originally isolated from either the rhesus or cynomolgus monkey [38].

A total of 46 picornavirus isolates were recovered from chimpanzees by SOIKE and his coworkers [17]. These were subdivided into five coxsackie A viruses and 41 other 'enteroviruses'. These viruses perhaps should be referred to as enteric viruses (in view of their recovery from the alimentary tract) rather than 'enteroviruses' until characterized. The coxsackievirus designation was based upon the type of histopathology (myositis) produced in newborn mice as well as the serological exclusion of poliovirus types 1-3, coxsackieviruses type A9 and types B1-6 as well as echovirus types 1-26 and type 28. Serum neutralization tests showed neutralization with antisera prepared against cox-

sackieviruses A 13 and A 18. It is not clear at this time why these two coxsackieviruses should show an antigenic relationship to the chimpanzee isolates. These coxsackieviruses are recovered relatively infrequently, are not known to be highly pathogenic, at least for man, and were originally isolated in remote areas, i.e. the type 13 in Mexico, and the type 18 in Africa. This latter finding may, however, have some relevance. Other agents with the characteristics of picornaviruses were also recovered which were not neutralized by any of these antisera. A number of the isolates evidently produced infection in the chimpanzees as homotypic antibody was demonstrated in convalescent sera.

*Reoviruses* (table II). Infection of chimpanzees with this group of agents is evidently commonplace. All chimpanzees were found consistently to show evidence of antibody to all 3 prototypes with some indication of persistent virus shedding, as chimpanzees born into the colony were found to be approximately 96.0% positive. Substantial confirmation of this finding was observed in testing with simian reovirus types 12 (Reovirus 1) and 59 (Reovirus 2). It will be recalled that SABIN [48] isolated an agent, later shown to be a reovirus [49] type 2, from a chimpanzee during an epidemic of rhinitis occurring in these animals. More recently ROGERS *et al.* [39] described the isolation of two reoviruses (Pan viruses 3 and 4) from the mesenteric lymph nodes and brain of chimpanzees involved in a kuru study [50]. These two strains of reoviruses apparently are closely related to existing recognized prototype reoviruses: Pan 3 to reovirus 2 and Pan 4 to reovirus 1. SOIKE *et al.* [17] have also isolated reoviruses from chimpanzees. A total of 6 isolates were described and classified as reoviruses on the basis of their antigenic relationship to type 1 reovirus.

Table II. Serologic results with representative reoviruses

Virus	Type of Test	S.F.R.E. <sup>2</sup>					Lab #1		Lab Born	Lab 1967	Lab #2	Lab #4	Lab #7
		Pre	1	2	3	4	1963	1966					
Reo 1	HI <sup>1</sup>	5/17 <sup>3</sup>	5/16	6/17	1/15	2/16	6/17	28/41	26/27	35/65	15/23	14/29	8/24
Reo 2	HI	3/17	5/16	6/17	1/15	1/16	7/17	34/41	26/27	45/65	4/23	6/29	8/24
Reo 3	HI	15/17	13/16	14/17	10/16	10/15	5/20	6/30	25/27	32/55	4/22	23/30	15/24
SV 12	HI	15/17	9/15	17/17	4/16	3/15	2/13	19/24	19/26	29/62	8/23	25/30	12/24
SV 12	SN						20/52				5/24		
SV 59	HI						7/17	33/41	26/27		4/23		

1 See table I.

2 See table I.

3 See table I.



*Myxoviruses* (table III). Problems arise when attempting to evaluate antibody responses to certain members of this virus group. For example, testing by complement-fixation (CF) and hemagglutination-inhibition (HI) procedures yield results that are apparently due to other factors than those recognized to be associated with detection of antibody. The question of nonspecific inhibitors present in nonhuman primate serum appears to be in need of study for a more complete and better evaluation of the observed findings. While only a few animals manifested evidence of influenza infection, the occurrence of chimpanzees with occasional positive findings emphasizes the possible role nonhuman primates may play in the maintenance of this disease in nature. Most common chimpanzee myxovirus infections, while they may vary among the different facilities, are RS, parainfluenza types 3 and 2 (in that order of frequency), and measles (rubeola). As indicated above, RS virus (CCA) was originally recovered from chimpanzees with coryza [13]. Of five chimpanzee colonies tested for antibody to this virus, sero-positives ranged from an incidence of 0.0% to that of 74.2%. Parainfluenza findings were generally similar to those found with RS virus except that the highest incidence noted was 69.0% for parainfluenza type 3. This outbreak apparently occurred just prior to the collection of serum samples as this high incidence was found by both serologic test systems employed, i.e. CF and HI. Testing chimpanzee sera for antibodies to recognized simian parainfluenza viruses (SV 5 and SV 41) has been limited to one small group of 11 chimpanzees. Only one of these animals demonstrated the presence of antibody to the SV 5 virus.

Parainfluenza virus isolations have been reported by SOIKE *et al.* [17] with a number of the isolates being identified as SV 5. Other parainfluenza viruses may be present but supplemental studies are necessary for clarification. This finding, however, would corroborate the serologic data mentioned above.

Measles antibody, which is generally quite high in primate colonies (man, monkeys) never exceeded 39.2 % in chimpanzees. An interesting epidemiologic observation was the failure to find any evidence of infection due to this virus in the SFRE colony over a nine month period. However, these same animals, as will be emphasized below, seroconverted from negative to positive for rubella virus during this same period. The general incidence of mumps virus antibody was low except for one facility in which 73.3 % of the chimpanzees were found with antibody.

Foamy viruses have provoked a certain amount of interest among laboratory investigators primarily because of their consistent presence in cell cultures (especially kidney) of primate tissue and secondly very little is known regarding what these viruses are capable of causing in the way of illness. Seven proto-

type viruses are now recognized as derived from rhesus, cynomolgus, African greens, squirrel monkeys, galagos, and chimpanzees. Types 6 and 7 (pan 1 and 2) were recovered from kidney, thymus and sympathetic nerve explants of chimpanzees [39]. In serologic studies now in progress at this institution some data are available suggesting that only limited infection occurs with the first 3 types of foamy virus: 3 of 29 chimpanzees had SN antibody to type 3, none of 10 for type 2, and none of 9 for type 1. Studies are now in progress with additional foamy viruses in order to ascertain the total incidence of antibody to these viruses.

Table III. Serologic results with representative myxoviruses

Virus	Type of Test	S.F.R.E. <sup>2</sup>				Lab #1				Lab #2	Lab #4	Lab #7	
		Pre	1	2	3	4	1963	1966	Lab Born				1967
Inf. A	CF <sup>1</sup>	0/12 <sup>3</sup>	0/13	0/15		0/12	0/17	0/44	0/29	0/68	0/11	0/27	0/21
Inf. A(PR8)	HI	0/13	4/12	0/13	0/16	0/16	2/31	0/27	0/25	0/62	6/25	2/25	0/24
Inf. A <sup>1</sup> (FM <sup>1</sup> )	HI	0/13	0/12	0/13	0/16	0/16	0/31	0/27	0/25	0/62	2/25	2/25	0/24
Inf. A <sup>2</sup> (Jap <sup>2</sup> )	HI	0/13	2/12	0/13	0/16	1/16	1/31	1/27	0/25	3/62	22/25	6/25	0/24
Inf. B	CF	0/12	0/13	0/15		0/12	1/17	0/44	0/29	0/68	0/11	0/27	0/21
Inf. B (Lee)	HI	0/13	4/12	0/13	0/16	0/16	0/31	0/27	0/25	0/62	5/25	2/25	0/24
Para 1	CF	0/16	0/18	0/18		0/15	0/27	0/44	0/29	0/69	0/19	0/29	0/24
Para 1	HI	0/13	0/12	0/13	0/16	0/16	1/13	0/27	1/25	3/66	0/19	5/25	0/21
Para 2	CF	0/16	0/18	0/18		0/15	3/27	0/44	0/29	0/69	0/19	1/29	0/24
Para 2	HI	0/13	0/12	0/13	0/16	0/16	0/13	0/27	0/25	1/66	1/19	3/25	0/21
Para 3	CF	0/16	0/18	0/18		3/15	10/27	0/44	0/29	0/69	1/19	4/19	8/24
Para 3	HI	0/13	4/12	0/13	4/16	3/16	6/13	11/27	4/25	3/66	20/29	6/25	6/21
Measles	CF	0/16	0/18	0/18		0/16	0/23	0/44	0/16	0/69	0/20	0/30	0/23
Measles	HI	0/17	0/18	0/18	0/16	0/16	11/43	6/42	5/28	0/69	9/23	9/30	0/24
Mumps	CF	0/17	0/13	0/14		0/16	1/26	2/44	0/29	0/69	1/14	2/30	1/24
Mumps	HI	0/17	0/18	0/18	2/16	0/16	0/13	2/36	2/27	4/64	0/19	22/30	1/24
R. S.	CF	11/16	9/18	5/17		0/5	20/27	4/44	4/29	8/69	0/19	5/29	0/24
SV 5	SN						13/49				6/23		1/11
SV 41	SN						4/52				3/24		0/11

1 See table I; CF = complement-fixation.

2 See table I.

3 See table I.

*Adenoviruses* (table IV). Studies involving this group of viruses in chimpanzees have been rather limited. Serologic surveys have been performed primarily with the CF test, a test that reacts to the presence of a common group antigen. Thus, any antibody production as a result of adenovirus infection, regardless

of the type or strain, will in general be detected by this CF test. Of consequence, however, is the lack of knowledge reflecting persistence of this antibody as a result of infection with different specific adenoviruses.

As will be demonstrated below, adenovirus infection of primates is common. It is not too surprising, therefore, to find an extremely high incidence of antibody to this virus group. Detection of type specific antibody among chimpanzees has recently been initiated in this laboratory with some limited information available: 1. CF antibody to human adenovirus type 12 and SA 7, both oncogenic for newborn hamsters, have been demonstrated only to a limited extent; 2. infection with SA 7, an African isolate (African green monkeys), however, is probably very frequent as SN antibody was consistently present among all the chimpanzees tested; and 3. seroconversion to positive for the various adenoviruses studied occurs among animals maintained in captivity.

Pan viruses 5, 6 and 7 isolated by ROGERS *et al.* [39] appear to be adenoviruses although 'originally thought to be enterovirus like'. These 3 viruses share the common CF adenovirus group antigen but apparently are not related to human adenovirus types 1-31, nor simian viruses 1, 11, 15, 17, 20, 23, 25, 27, 30-34, 36-38. SOIKE *et al.* [17] has isolated adenoviruses, as yet not typed, from the chimpanzee as has ROWE *et al.* [51]. These latter investigators refer to their adenovirus isolate as C-1 (Strain Bertha).

Table IV. Serologic results with representative adenoviruses

Virus	Type of Test	S.F.R.E. <sup>2</sup>				Lab #1				Lab Born	Lab #2	Lab #4	Lab #7
		Pre	1	2	3	4	1963	1966	1967				
Adeno Grp.	CF <sup>1</sup>	8/16 <sup>3</sup>	7/18	9/18		14/15	20/32	32/34	21/29	28/69	16/18	27/29	18/24
Adeno 12	CF	2/14				2/16	0/23	0/44		0/69	1/20	0/30	0/22
Adeno 12	SN									0/26	9/23	3/11	
SA 7	CF					2/16	0/23	0/44	0/26	0/69	0/20	0/30	0/22
SA 7	SN	1/14	3/17				16/54			11/21	1/6	12/23	
SV 1	SN		4/17				3/51				1/24	2/11	
SV 15	SN		2/18				6/52			0/25	10/24	0/11	9/25
SV 39	SN		0/18				2/52			3/20	0/20		
V 340	SN		5/17				7/51			9/22	0/8	3/11	

1 See table I.

2 See table I.

3 See table I.

*Arboviruses* (table V). Little evidence of infection by arboviruses common to the U.S., i.e., Western and Eastern encephalitis and St. Louis, was found in a survey performed in this laboratory [38]. OSTERREITH *et al.* [52] reported finding antibody to Chikungunya virus in wild chimpanzees in the Congo. As mentioned above, HARRISON *et al.* [46] reported on serologic evidence for infection of chimpanzees with Chikungunya and related viruses. These investigators reported finding SN antibody to this virus group in wild born as well as in chimpanzees born in the U.S. Some evidence that infection with related Group A arboviruses does occur, however, was finding antibody to WE in this same colony of chimpanzees. This finding of WE antibody in chimpanzees has been confirmed in studies done on other primates (baboons) maintained under similar conditions [38, 53].

Perhaps more important than this general low level of detectable antibody to these viruses is the failure to find antibody in chimpanzees arriving from areas known to be yellow fever endemic sites. While the absence of antibody is a good indication for the lack of contact with this virus, U.S. Public Health Service requirements make it mandatory to either vaccinate or take other appropriate precautions to prevent yellow fever virus from gaining entry into the U.S. In a study recently completed in this laboratory [54], it was found that many nonhuman primates, including chimpanzees, arrive in the U.S. without antibody to yellow fever although presumably previously vaccinated.

Table V. Serologic results with representative arboviruses

Virus	Type of Test	S.F.R.E. <sup>2</sup>				Lab #1							
		Pre	1	2	3	4	1963	1966	Lab Born	1967	Lab #2	Lab #4	Lab #8
EEE	CF <sup>1</sup>	0/17 <sup>3</sup>	0/18	0/14		0/14	0/26	0/44	0/29	0/69	0/14	0/13	0/24
WEE	CF	0/17	0/18	0/14		0/14	2/26	0/44	0/29	0/69	0/14	0/29	0/24
SLE	CF	0/17	0/18	0/14		0/16	0/21	0/44	0/29	0/69	0/12	0/30	0/24
YF	CF						1/25				1/17		

1 See table I.

2 See table I.

3 See table I.

*Herpesviruses* (table VI). This group of viruses has held the attention and concern of investigators employing simians since SABIN and WRIGHT [55] described the occurrence of a fatal disease in man following a monkey bite. Serologic studies for antibody to this virus group are very limited and in need of evalua-



tion. For example, 293 chimpanzee sera from 5 different colonies have been examined with only 5 of the animals possessing CF antibody to the *Herpesvirus hominis* antigen. Perhaps most important was the change observed in the 15 chimpanzees in this colony. These animals were negative to this herpesvirus upon arrival but by the 4th bleeding, approximately 6–9 months after arrival, 4 of the animals became seropositive. Once again it is to be emphasized that CF testing may not depict the true infection status of an animal as these antibodies are generally of short duration and cross reactions are commonplace. Equally important, therefore, are the cross reactions observed when attempting to define the serologic parameters manifested by this group of viruses. Determination of specific antibody is extremely difficult, requiring quantitative type tests for differentiation of the strains. Routine serologic procedures as currently employed cannot be considered as sensitive enough to differentiate the various strains of herpesviruses making clear-cut, specific determinations practically impossible. Thus, finding 9 of 67 chimpanzee sera to be positive in the SN test to *Herpesvirus simiae* raises the question as to the origin of this antibody – simplex or simiae? This is emphasized by finding in another study (on baboons) that this increase in antibody incidence is related directly to the aging of the animals. Animals newly imported or newborns rarely, if ever, have herpesvirus antibody but after several years in captivity become serologically positive without ever manifesting any clinical evidence of disease. Also as indicated above, the serologic change in the chimpanzees maintained at SFRE appears to be due to simplex rather than simiae. Clinical disease has never been noted in these chimpanzees or reported by other investigators as present in other colonies of chimpanzees.

Recently an interesting observation was reported by LANDON *et al.* [56] on the presence of herpes-type virus particles in chimpanzee cultured leucocytes. Long-term cultures of chimpanzee leucocytes derived from chimpanzees inoculated with human cell lines obtained from Burkitt's lymphoma as well as uninoculated control animals demonstrated a herpes-type virus. Chromosome karyotyping suggested possible contamination of *one* of these cultures with human cells. These investigators suggest the following interpretations for the finding of herpes-like virus in these cells: 1. they are passenger viruses unrelated to the lymphoma under study; 2. the viruses are causally related to the disease and a chimpanzee will develop a malignancy; or 3. there is a relationship between this virus and lymphoma and the chimpanzee is serving as a carrier rather than a host.

It would appear that additional studies are required in order to satisfactorily explain these findings. Herpes-like particles have been reported from a

multitude of clinical conditions as well as in numerous types of human tumors. In this regard the recent studies by the HENLE's are important [57]. These investigators suggest that the agent they have recovered from Burkitt's tumor is an unknown member or type of herpesvirus and is evidently disseminated in man. Furthermore, the HENLE's have tested a number of control sera from various primates: rhesus monkeys, baboons, and chimpanzees with negative results. However, a cooperative study done with baboons in this laboratory showed 2 of 4 baboons developing low levels of antibody against inoculated Burkitt lymphoma culture cells containing herpes-like virus. The need for additional studies with a variety of primates is obviously essential.

Table VI. Serologic results with representative herpesviruses

Virus	Type of Test	S.F.R.E. <sup>2</sup>					Lab #1						
		Pre	1	2	3	4	1963	1966	Lab Born	1967	Lab #2	Lab #4	Lab #7
Herpes Simp. CF <sup>1</sup>		0/15 <sup>3</sup>	0/18	0/14		4/14	1/26	0/43	0/28	0/69	0/14	0/28	0/24
B virus	SN										9/67 (Labs 1 & 2)		

1 See table I.  
2 See table I.  
3 See table I.

*Miscellaneous* (table VII). A number of additional viruses, virus groups and other agents have been investigated with regard to chimpanzees.

*Rubella*. This virus has not been recovered from normal chimpanzees although its presence has probably not been actively investigated. As this agent is rather universal it was of interest to assay chimpanzee sera for rubella antibody. It may be noted that there is a rather high incidence of positive animals (48.7%) among the various colonies tested. As pointed out previously it was epidemiologically interesting to note that a number of these animals converted serologically from negative to positive during their stay at this facility as well as in another colony. However, baboons maintained at SFRE during the same period did not show this seroconversion. It will be noted further that the converse for rubeola was observed with regard to the two different groups of animals, i.e. chimpanzees and baboons at SFRE. It is assumed that this difference resides in the maintenance of two completely independent animal groups separated by distance as well as by use of animal handlers.

Table VII. Serologic results with representative miscellaneous agents

Virus	Type of Test	S.F.R.E. <sup>2</sup>					Lab #1		Lab		Lab #2	Lab #4	Lab #7
		Pre	1	2	3	4	1963	1966	Born	1967			
Rubella	HI <sup>1</sup>	4/12 <sup>3</sup>			13/13	14/14	0/8	15/32	1/14	28/47	4/5	13/20	3/21
Vaccinia	HI	0/14	0/17	0/18	3/16	2/16	0/8	0/41	0/23	0/60	0/6	0/29	
Monkey Pox	HI	4/14				3/13		2/21	0/14	9/69	0/6	5/30	2/24
SV 40	SN		0/18				0/51			0/17	0/24	0/22	2/25
LCM	CF	0/17	0/18	0/18		0/16	0/21	1/44	0/29	0/69	2/12	0/29	0/23
Marburg Virus	CF	2/15					0/21	1/34	0/27		1/4	0/30	
SHF <sup>4</sup>	CF									0/69		0/23	
Psitt-LGV Group	CF	1/17	0/18	0/14		0/16	0/21	0/44	0/29	0/69	0/11	0/30	0/24
Q-Fever	CF	3/16	2/18	1/18		7/15	17/20	1/44	1/29	0/69	2/18	4/30	1/24
Spotted-Fever	CF	2/15				1/16	0/42	1/39	0/25	0/69	0/20	2/29	0/22
Rickettsial-Pox	CF	0/15				1/16	0/42	1/39	0/25	0/69	0/20	3/29	0/22
PPLO	CF	4/16	5/18	7/18		2/15	6/26	20/44	1/29	2/69	8/14	9/30	2/24

1 See table I.

2 See table I.

3 See table I.

4 Simian hemorrhagic fever virus (unpublished data).

*Poxviruses.* Various members of this virus group are capable of inducing infection and disease in a multitude of mammalian and avian hosts. Unfortunately, the interrelationships between various members of the poxviruses are little understood. There is a possibility that an animal reservoir exists for this virus group with an interchange of organisms between species precipitating outbreaks. While the epidemiologic data for this supposition is scanty, the close antigenic relationships between members of the poxviruses are well established. Furthermore, considerable attention has been given this virus group because tumor-like growths have been observed in monkeys (58) following infection with at least one member of the group (Yaba virus).

In this laboratory it has been found that comparative testing of sera in the HI test employing vaccinia virus and monkey pox virus antigens results in the detection of more positives with the latter antigen. Very few seropositives were obtained among chimpanzees with the CF test regardless of the antigen employed. Monkey pox has been reported in chimpanzees and our serologic

findings show an incidence of 13.1 % infectivity. All colonies but one (only 6 chimpanzees tested) had animals with demonstrable HI monkey pox antigen. Very few of the chimpanzees (all in one colony) demonstrated antibody to the vaccinia virus. Occurrence of a poxvirus disease in chimpanzees has been noted [43]. An epizootic of pox disease has also been reported as spontaneously occurring among all the apes and monkeys at the Rotterdam (Blijdorp) Zoo [59]. In this instance the giant anteater, *Myrmecophaga tridactyla* was the source of the virus. Therefore, a 'monkey pox' virus may not have been involved.

The recent studies by MCCONNELL and his collaborators [60, 61] are of importance with regard to poxvirus infections of simians. These investigators have now demonstrated that immunization of rhesus monkeys [60] and chimpanzees, *Pan satyrus* [61], with vaccinia virus is highly successful in protecting these animals against monkey pox virus infection. In our hands (unpublished data) very close serologic agreement has been demonstrated between monkey pox and vaccinia antigens in the HI test.

*Papovavirus (SV40)*. 97 chimpanzees in 3 different colonies have been tested for the presence of antibody to this simian virus with negative results. This finding is somewhat surprising in view of the generally high incidence of antibody as well as virus isolation found in other nonhuman primates. As this virus is the only known simian virus other than certain of the simian adenoviruses that produces tumors in newborn hamsters further studies relative to the relationship of this virus to primate disease is important.

*Lymphocytic choriomeningitis (LCM)*. A disease primarily of rodents, this virus is capable of producing a severe central nervous system disease of man. Its potential in other primates, however, has not been studied to any extent. Antibody to this virus has been found only to an extremely limited extent among chimpanzees, i.e. 3 of 296 sera tested ([38], unpublished data). However, one colony of 12 animals had 2 chimpanzees with antibody. Since the CF test was employed it would appear that these infections were relatively recent. Infection (if not disease) of the animals probably occurred via contamination of food supply by mouse urine or feces.

*Marburg virus (African Green Monkey Disease)*. The recent outbreak of disease with a number of deaths among laboratory workers employing African green monkeys has caused great concern among investigators using simians. A virus has been isolated (in guinea pigs) from patients with the disease [62]



and a serologic survey for the presence of antibody among various primates completed [63]. A number of primate sera from African animals including the chimpanzee (4 of 111 tested) demonstrated CF antibody to this agent. No antibody was detected to the Marburg virus in human sera and very few non-African primates showed the presence of this antibody. African primates born in the U.S. (chimpanzees, baboons) also did not have antibody to the Marburg virus. A much greater incidence of antibody was detected among such African primates as the African green and talapoin monkeys included in this study.

*Infectious hepatitis.* The etiologic agent of virus hepatitis has not been identified although there does not appear to be any doubt regarding a virus relationship. One aspect of this disease that has caused concern among investigators employing simians, especially chimpanzees, was the report by HILLIS in 1961 [37] regarding the extremely high attack rate of hepatitis in veterinarians and animal handlers handling young and newly imported chimpanzees. A number of reports have since documented this observation. Reinforcing the role of the chimpanzee in the spread of hepatitis has been the finding of spontaneous disease occurring among these animals [64, 65]. The exact relationship of the chimpanzee to this disease is not clear; however, it is highly probable that the animals contact virus in their native habitat and then shed the virus for some time subsequent to capture. Clinical disease in the chimpanzee is apparently rare. SMETANA [65] reported a young male chimpanzee, approximately 2½ years old, developed clinical viral hepatitis: fever, anorexia, diarrhea, vomiting, jaundice, and characteristic liver function test findings. The animal died 4 days after presenting clinical symptoms. Autopsy findings were compatible with the diagnosis of acute fulminant viral hepatitis.

*Psittacosis-lymphogranuloma venereum group (Psitt-LGV).* These agents are not considered as true viruses but rather as an intermediary group between the viruses and the rickettsiae. This group is now referred to as '*Bedsoniae*' commemorating Bedson's comprehensive study of the psittacosis agent. Studies concerning these organisms are very limited. Evidence of infection by members of this group have not been found naturally occurring in chimpanzees. Serologic evidence for presence of antibody in the chimpanzee, as previously reported [38] and recently expanded [unpublished data], has failed to find any positive animals except for one specimen. This single animal was one recently captured and found positive upon initial bleeding. Seroconversion of this animal to negative after a few months in captivity emphasizes the importance of the type of test used for antibody surveys.

*Rickettsiae*. Only brief mention is made of these organisms, primarily because of their phylogenetic relationship to the viruses and because of their occurrence in various arthropods in nature. No information is available regarding natural rickettsial diseases among chimpanzees. A relatively high incidence of antibody among primates to various *Proteus* strains of bacteria (positive Weil-Felix reactions) suggests additional specific studies. However, extensive testing of chimpanzee sera for antibodies to Rocky Mountain Spotted Fever (*Rickettsia rickettsi*), Rickettsialpox (*R. akari*), epidemic (*R. prowazeki*) and endemic (*R. mooseri*) typhus have failed to find any evidence of recent infection. Q fever (*Coxiella burneti*) antibodies, however, are quite common, especially among newly captured chimpanzees ([38], unpublished data).

*Miscellaneous virus isolations* (table VIII). A listing of virus isolations is presented primarily to indicate the type of findings encountered (unpublished data). This information is preliminary and still under study. It may be seen that enteroviruses predominate in all the chimpanzee colonies examined. Other virus groups are scattered but cursory examination suggests that the adenovirus findings are lower than one would anticipate. Also certain isolates need further study in order to ascertain whether or not they were recovered from the chimpanzee specimens or were tissue culture contaminants.

Table VIII. Chimpanzee virus isolates. Tentative grouping

	Entero	Adeno	Myxo	Papova	Unclass.	Total
S.F.R.E.	3	1 <sup>2</sup>	—	—	2	6
Lab. #1 (a)	22	—	5	—	12	39
Lab. #1 (b)	93 <sup>1</sup>	4	10	19	10	136
Lab. #2	40	—	—	—	—	40
Lab. #4	2	—	—	—	7	9
	160	5	15	19	31	230

1 Includes: 2 — Polio type 1; 1 — Polio type 2; 6 — Polio type 3.

2 Possibly SV37 — not confirmed.

#### EXPERIMENTAL INFECTIONS OF 'NORMAL' CHIMPANZEES

Early utilization of chimpanzees for experimental virus studies has been mentioned. It is to be reiterated that a number of studies using one or another simian did occur prior to the interest in poliomyelitis but it was the use of

tissue culture for poliomyelitis research that resulted in the current extensive use of nonhuman primates in virus studies. In most instances the simians employed were rhesus and/or cynomolgus monkeys. Gradually more widespread usage of nonhuman primates expanded to include representative species of monkeys and apes. Frequently the various apes could be considered as the more desirable choice of experimental animal but expense and general unavailability has limited any major inclusion of these simians into large programs. Nonetheless, as will be described below, a number of experimental virus studies have included the chimpanzee. Experimental use of chimpanzees in virus studies are briefly described below.

*Picornaviruses.* The early studies of HOWE and BODIAN [24, 29–33] relating to experimental production of poliomyelitis in chimpanzees have been cited. These studies, along with those of TRASK and his coworkers [66, 67] established the susceptibility of man and chimpanzee to infectivity by poliovirus. The chimpanzee, like man, was shown to be susceptible to poliovirus infection by small amounts of virus administered orally. Enteric infection resulted with only occasional establishment of central nervous system invasion. Virus given parenterally also found its way to the intestinal tract. Overt disease due to poliovirus of chimpanzees is now recognized. MELNICK [68] demonstrated that virus could be recovered from the stool of experimental animals prior to development of CNS disease. Furthermore, he demonstrated that a 'healthy' carrier state could be produced in chimpanzees following intracutaneous inoculation of virus. Similar events occurred following inoculation of chimpanzees with various members of the coxsackievirus group: Types A 2, 3, 4 and 12; Types B 1, 2 and 3. Inapparent infection with recovery of virus from the throat and virus shedding in feces regularly occurred following inoculation of animals. Inoculation of chimpanzees with various echoviruses, types 2, 3, 4, 6 and 9, either orally or parenterally failed to produce clinical disease. ITOH and MELNICK [69] administered various echoviruses by different routes with the production of an inapparent infection characterized by a transient viremia and virus excretion from throat and in feces with a subsequent antibody rise. Similar studies have been performed by YOSHIOKA and HORSTMANN [70] with echovirus 9. Echovirus 4 was particularly interesting in that virus excretion in the chimpanzee pharynx exceeded that of the intestines as recovered in feces.

Rhinoviruses are included, along with the enteroviruses, among the picornaviruses as they share numerous biologic characteristics in common. Clinically, these viruses tend to produce respiratory rather than enteric disease, probably because of their sensitivity to low pH. Rhinoviruses are closely

associated with the common cold, man being the only known natural host. However, DOCHEZ and his collaborators [71, 72] were able to demonstrate that chimpanzees contract 'colds' from human contacts and that the symptomatology was in general similar to that observed in man. More recently, DICK [73] infected a number of chimpanzees with rhinoviruses type 14 and/or 43. These animals did not manifest any clinical symptomatology but did shed virus for 6–21 days and produced high levels of antibody.

In 1945 HELWIG and SCHMIDT [74] reported on the recovery of a virus by inoculating mice with chest fluids and splenic tissue obtained from a chimpanzee dying from acute cardiac failure and pulmonary edema. This isolate produced paralysis and interstitial myocarditis in the inoculated mice. Subsequent studies by SCHMIDT [75] demonstrated that this virus was mildly infectious for chimpanzees and had little or no pathogenicity for man. This encephalomyocarditis (EMC) virus was later found to be immunologically related to Columbia – SK and MM viruses, and these viruses, as a group, are now included among the picornaviruses.

*Reoviruses.* SABIN [49] reported in 1960 an outbreak of upper respiratory disease occurring among chimpanzees due to reovirus type 2. Chimpanzees without antibody to this virus responded with the same syndrome following intranasal inoculation of cultured virus. Isolation of virus from throat and feces was possible for approximately two weeks post inoculation.

*Myxovirus.* As indicated previously, there are a number of problems associated with any attempt to interpret results following infection, either natural or experimental, by the various members of the myxovirus group. This is a large group of viruses and, certainly as a group, infection of nonhuman primates occurs. Which myxoviruses are capable of producing infection and/or disease is in need of resolution. Antibody has been found to a number of the myxoviruses in a variety of nonhuman primates – the exact meaning of these findings is not clear – furthermore, evidence is accumulating which indicates wide-spread infection by various myxoviruses of various species animals and birds, notable exception having been noted. For example influenza has been reported in chimpanzees [76] but no definitive evidence other than clinical is presented. Experimental infection of macaques has been induced, however, with variable results [77–79]. Similar studies, to our knowledge, have not been attempted in chimpanzees. The parainfluenza viruses are another example of lack of information. There are two recognized simian parainfluenza viruses – SV5 and SV41; neither these nor the human strains have been studied ex-



perimentally in chimpanzees. HSIUNG *et al.* [80] did study chimpanzee sera for antigenic relationships among several of the myxoviruses as well as antibody development to the DA virus and other parainfluenza viruses. No attempt was made to study the invasiveness of these viruses. Mumps and measles viruses have been studied only to a limited degree in monkeys and not in higher apes. However, RS virus produces evidence of apparent disease in chimpanzees following experimental inoculation [81]. Upper respiratory tract disease without fever occurs in the chimpanzee. Other animals including various monkeys were also tested but without production of illness. The original report of MORRIS *et al.* [13] with regard to RS virus is again emphasized.

*Adenoviruses.* These viruses have not been studied experimentally in chimpanzees although a large number of simian adenoviruses are recognized. As described above, a number of these viruses have been recovered from captive chimpanzees [17] and evidence for the presence of adenovirus antibody has been reported [38].

*Arboviruses.* The close relationship of arthropod-borne viruses to simians all over the world would suggest that extensive experimental studies involving apes and monkeys probably had been performed. This apparently is not so. While various monkeys have been used in a number of studies, little in the way of experimental infection is found for these animals and less for the chimpanzee. THOMAS in 1907 [21], studying yellow fever, allowed experimentally-fed mosquitoes to bite a chimpanzee which in turn developed a characteristic illness as well as resistance to reinfection. Other experimental studies concerning yellow fever in chimpanzees followed: PETTIT and AUGESSY [82] demonstrated development of protective antibody in chimpanzees as a result of inoculation with the French strain of yellow fever virus. The studies of FINDLAY and his coworkers [83] demonstrated infection of chimpanzees under natural conditions. Experimentally induced disease of chimpanzees with yellow fever virus was also demonstrated by SMITHBURN and HADDOW [84].

*Herpesviruses.* Experimental inoculation of chimpanzees with the various herpesviruses does not appear to be extensive. However, herpes-like viruses or particles have been described as associated with various tumors especially that referred to as the Burkitt tumor [85]. The HENLE's [57] have used immunofluorescence to detect the presence of these herpes-like particles in various tissues or for detecting the presence of antibody to the particles. Control sera from numerous nonhuman primates including chimpanzees were negative for

this antibody. These investigators (personal communication) are now attempting to ascertain the response of various nonhuman primates to these particles.

*Miscellaneous.* It is apparent from the above that only limited usage has been made of the chimpanzee as an experimental animal for the study of virus infections. Two notable exceptions are briefly described:

*Infectious Hepatitis (IH).* The association of human illness with chimpanzees [37] prompted exploration into possible use of this animal for studies related to the pathogenesis of IH. There have been reports suggesting that the chimpanzee does become infected with this virus [65, 86, 87]. Questions have been raised, however, relative to what constitutes infection by IH virus in chimpanzees. Various coincidental changes, similar to those described as occurring in man, have been similarly described in the chimpanzee. Similar pathologic changes, especially in the liver, have also been reported.

The findings of SMETANA [65], for example, while suggesting occurrence of experimental hepatitis in patas monkeys and spontaneous disease in chimpanzees, notes that the test chimpanzees did not respond to virus (human volunteer blood plasma) challenge. This failure to induce hepatitis in the chimpanzee was considered to be due to an immunity, possibly induced by a previous infection of the animals. Similarly, the experimental efforts by DOUGLAS and BERGE [86] to produce hepatitis in chimpanzees using viruses recovered from human cases also were not considered as conclusive. On the other hand, ATCHLEY and KIMBROUGH [87] described transaminase elevations and pathologic changes similar to those occurring in human cases of infectious hepatitis in five of six chimpanzees experimentally infected with human material or feces from one of the infected chimpanzees. As a continuation of this study, HARTWELL *et al.* [88] found that chimpanzees with hepatitic lesions diagnosed as acute viral hepatitis, had considerably higher SGOT and SGPT values than normal chimpanzees. It would appear that continuation of these studies are necessary for further evaluation of the response of chimpanzees to the virus of infectious hepatitis.

*Kuru.* A disease of humans occurring in a limited area of New Guinea and characterized by a familial degeneration of the nervous system [89]. This disease is now believed to be caused by one of the slow viruses similar to such diseases as scrapie and possibly a number of other degenerative diseases of the central nervous system. Also quite noteworthy is the failure to isolate this virus in any laboratory animal except the chimpanzee [90], although two sep-

arate studies have suggested mice [91] and baboons (unpublished data) may also be susceptible. In the chimpanzee, patient material (brain) initiated characteristic symptomatology generally in 18–30 months. Illness persisted for 5–9 months, terminating fatally after the occurrence of complete paralysis. Chimpanzee to chimpanzee transmission of the disease has been successfully accomplished.

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#### SUMMARY

Biomedical research has reached that stage of development whereby non-human primates are given serious consideration as the experimental animal of choice, substituting in many instances for other animals long associated or considered as models for laboratory studies of human disease. More than likely this consideration has stemmed from the realization that animal experimentation is unwise when the study under consideration is unnatural or biologically remote for the animal chosen. In order to relate experimental results with diseases of man or other primates it would appear that selection of an animal phylogenetically closer to man than the mouse or guinea pig would be apropos. This consideration, while still extremely limited in scope, has had a profound impact on biomedical research. Entirely new concepts and vistas have unfolded, initiating a contribution to comparative medicine heretofore unrealized.

It is necessary, for the inclusion of primates as a laboratory tool notwithstanding, to interject a word of caution. The scientific community must recognize the existence of a limited number of inherent problems associated with use of these animals. In developing an experimental animal closely related to man it goes without saying that any microbial interchange must be

considered as a two way exchange. The fact that various simians are known to harbor agents pathogenic for man must be carefully taken into consideration. Rationalization such as the known human attack rate has been limited or very infrequent is indeed imprudent. When deaths of  $\frac{1}{3}$  or higher occur in those attacked, precautions preventing such events must be considered. Further contemplation must be given to developing an understanding and control of zoonotic diseases of nonhuman primates and their human counterparts.

The close relationship of the chimpanzee to man has been well established both in fiction and biologically. The data described herein substantiates this consideration in demonstrating that infection and/or disease with many of the recognized human viruses and virus diseases occur with frequent regularity. A virus relationship with other simians likewise has been developed. Existence of infectious agents other than viruses also must be recognized. Probably of greatest concern to laboratory workers are infections due to *Herpesvirus simiae*, infectious hepatitis and more recently the disease associated with the Marburg virus (African Green Monkey Agent). Of these three clinical problems, the chimpanzee has been involved only with infectious hepatitis with regard to human infections. The potential threat posed by the other two entities remains an unknown factor although antibody to both agents have been demonstrated in chimpanzees [38, 63]. The significance of findings such as these is obscure at this time; however, inasmuch as other simians have been directly involved every consideration must be given to the possible association of chimpanzees with these animals in the wild and after capture. The potential of other agents, for example cytomegalovirus which has not been studied in the chimpanzee, requires consideration.

In reviewing the virus status of chimpanzees it becomes apparent that only cursory information is available with regard to natural and experimental infections. Preliminary indications suggest that virus relationship to man may be considered as a potential if not already established. However, actual epidemiologic and ecologic relationships are far from clear. Furthermore, little, if any, information is available relating to the pathogenesis of the various viruses. Recovery of human agents from the chimpanzee establishes the existence of cross infection. The significance of this finding is unfortunately not clear but does emphasize an intimate relationship between man and chimpanzee. The possibility exists that one of these isolates recovered from the chimpanzee may be that of infectious hepatitis. It is also conceivable that certain of the agents may be tumorigenic – for what host is probably not important at this time. Continued study is imperative in order to characterize or perhaps clarify the



status of existing isolates. Other, still unisolated, agents are undoubtedly present in various tissues and body fluids awaiting perhaps more sophisticated technical approaches for their discovery. It also would be of interest to determine the virus flora of chimpanzees in their native habitat. This has been done only to a very limited extent and then primarily ancillary to other studies. A point that must be reemphasized is that the chimpanzee data described herein are derived mainly from captive animals. Of importance would be longitudinal studies on a sizable group of animals from time of capture through an extensive period of confinement. As a corollary, the effect of shipment, exposure to other animals (both chimpanzees and other primates – including man) and so on would be of immeasurable assistance to furthering our understanding. Evidence for the need of such studies stems from the report of SOIKE *et al.* [17] as well as data from this laboratory, demonstrating the presence of human viruses in chimpanzees after contact with man. This possibility is emphasized by SOIKE *et al.* [17] in suggesting that their coxsackie group A viruses may have been derived from one of the personnel working with the animals. Perusal of their data stresses this role of human transfer of agents to the chimpanzees. No information relative to transfer of chimpanzee agents to man was presented. Other studies have been mentioned in the text that underscore this concept.

In developing this background of information on the chimpanzee one consideration in need of discussion concerns the laboratory techniques employed for the collection of these various data. It is accepted that many viruses will grow in a variety of cell culture systems, if not in the host supplying the cells. It is also accepted that there is a certain amount of host-parasite specificity concerned with cultivation of viruses and each virus may require its own particular host cell system. Failure to isolate or recover an agent from a specimen may simply be a reflection of this lack of host cell susceptibility. Choice of cell system is, therefore, of obvious importance for the satisfactory study of viruses in an animal such as the chimpanzee. It would have been more satisfactory if chimpanzee cells, in addition to those cell systems used, were employed for certain of the studies described herein. Unfortunately, this capability is frequently not feasible as collection of the necessary tissues may imply sacrifice of the animal. Complicating this problem is the fact that primary systems are generally preferable to serial cell lines. The availability of a number of chimpanzee serial cell lines, therefore, does not adequately provide the satisfactory supply of the necessary tissues [92, 93].

Lastly, brief mention should be made regarding use of primates, especially the chimpanzee, for studies on chronic central nervous system diseases. Trans-

mission of the virus of kuru in these animals emphasizes the potential of non-human primates not only for the study of degenerative disease but for the numerous other 'infectious' illnesses of mankind in need of study.

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Authors' addresses: S. S. KALTER, Division of Microbiology and Infectious Diseases, Southwest Foundation for Research and Education, *San Antonio, TX (USA)*.  
N. B. GUILLOU, Yerkes Regional Primate Center, *Atlanta, GA (USA)*.

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# THE ISOLATION OF MYCOPLASMAS FROM CHIMPANZEES

B. C. COLE, C. E. GRAHAM and J. R. WARD

Department of Internal Medicine, Division of Arthritis,  
University of Utah College of Medicine, Salt Lake City, UT,  
and Yerkes Regional Primate Research Center,  
Emory University, Atlanta, GA

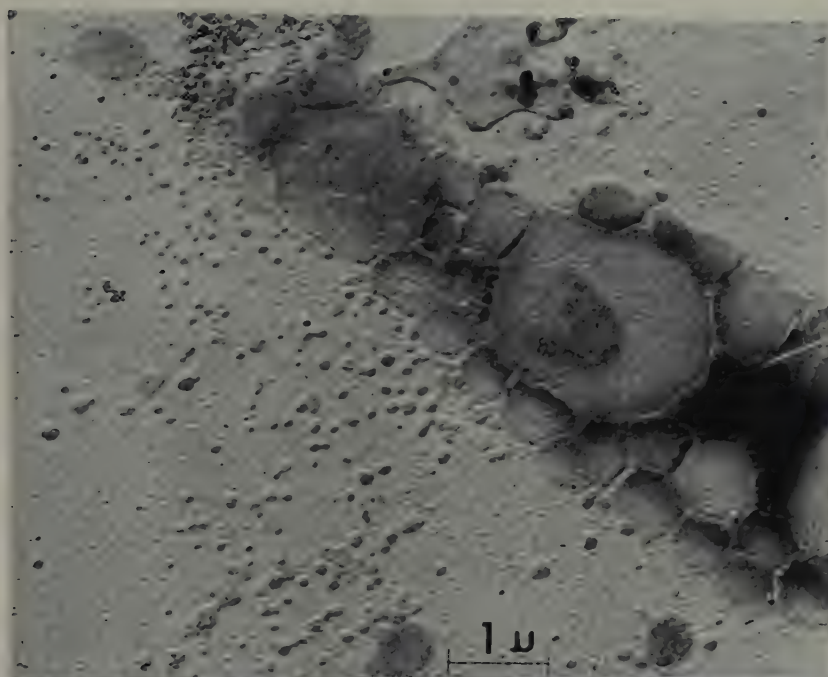
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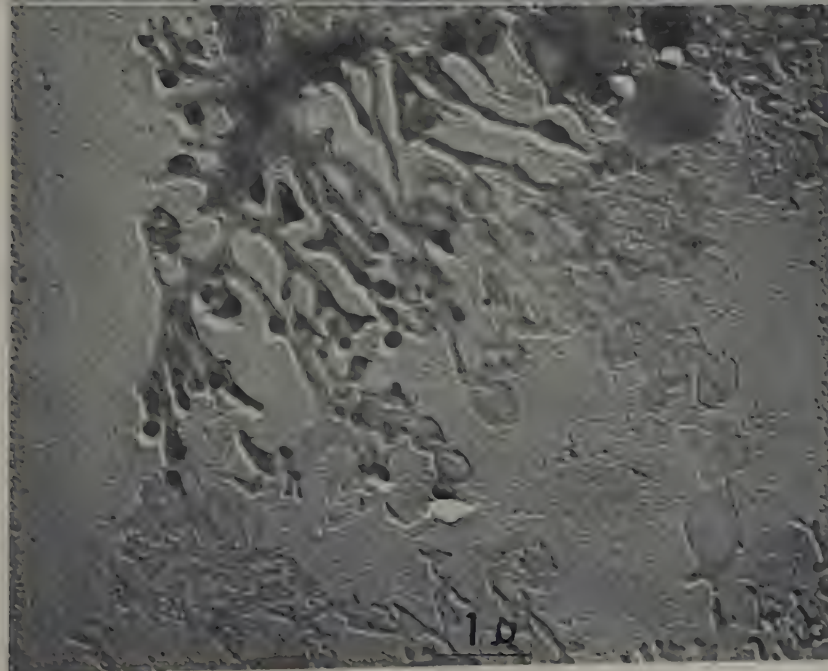
## GENERAL CHARACTERISTICS

The mycoplasmas, previously referred to as pleuropneumonia-like organisms (PPLO), are currently grouped in the order Mycoplasmatales within the class Schizomycetes. It has recently been proposed that these organisms be transferred to a new class, Mollicutes [17]. Mycoplasmas have a triple layered limiting membrane instead of a rigid cell wall which is characteristic of the bacteria. The absence of a rigid outer structure results in extreme pleomorphism and poor affinity for stains. Multiplication may be by binary fission, fragmentation of filaments or by the production of minimal reproductive units of 0.125  $\mu\text{m}$  in diameter (fig. 1 A, B). The plasticity of these organisms

*Fig. 1. A* Electron micrograph of *M. laidlawii* showing minimal reproductive units and large cells. The specimens was prepared by growing the organisms for 24 h on a collodion membrane, followed by shadowing at 18° with 40 % palladium/gold vapor. *B* Electron micrograph of a fresh isolate of *M. salivarium* showing the filamentous, branching mode of growth. Specimen prepared as above (reproduced from COLE, Diss. Birmingham, 1964).



4



B



often results in the production of artifacts during the procedures required for microscopic observation. For this reason considerable controversy still exists concerning their true morphologic and reproductive characteristics. Mycoplasmas are capable of growth in cell-free media and they represent the smallest free-living forms of life.

Most mycoplasmas have limited metabolic capabilities and require a complex medium consisting of inorganic salts, amino acids, carbohydrates, vitamins, nucleic acids, lipids and proteins. The addition of mammalian serum to a basic medium consisting of a beef heart infusion satisfies the growth requirements of most species. The more fastidious species may require the addition of fresh yeast extract, deoxyribonucleic acid, diphosphopyridine nucleotide or dextran.

#### ROLE IN ANIMAL AND HUMAN DISEASE

The first description of mycoplasma was that of NOCARD and ROUX who described the agent of bovine pleuropneumonia in 1898 [37]. Since that time mycoplasmas have been identified as the causative agents of agalactia of sheep, caprine pleuropneumonia, rat arthritis, swine arthritis and peritonitis, bovine mastitis, respiratory disease of fowl, neurologic disease of mice and respiratory disease of rats and mice. Other animal diseases are suspected of having a mycoplasmal etiology.

Not until 1962 were mycoplasmas shown to be pathogenic for man when the Eaton agent which causes primary atypical pneumonia (PAP) was shown to be a mycoplasma [6]. The organism was subsequently named *Mycoplasma pneumoniae* [7]. PAP has an incubation period of 1 to 3 weeks with initial non-specific constitutional symptoms of infection. Subsequently, respiratory symptoms of dry, hacking cough appear. Fever is usually present, there is moderate pharyngitis and fine to coarse rales may be heard at the end of expiration. The roentgenogram of the chest is usually characteristic with soft, hazy, diffuse and ill-defined mottled and reticular shadows which often rapidly change in appearance. Mortality is low. Complications are rare although encephalitis, meningoencephalitis, polyneuritis, myocarditis, pericarditis, hemolytic anemia and bronchiectasis have been reported. Of great interest is that the serum of about 70% of patients with PAP acquire an antibody which causes the agglutination of human type O erythrocytes at 0° to 10°C (cold agglutinins). The only known reservoir of the agent *M. pneumoniae* is man and it appears that prolonged close personal contact and a large popu-

lation of susceptible persons are the usual setting for mild epidemics. *M. pneumoniae* is also thought to be involved in myringitis and the Stevens-Johnson syndrome [21, 28, 30, 42, 45, 47].

The pathogenicity of other human mycoplasmas is somewhat in doubt. However *M. hominis* (type 1), a common inhabitant of the urogenital tract, may have an etiologic role in exudative pharyngitis and tonsillitis [34]. The association of *M. hominis* with non-gonococcal urethritis is still much in doubt. Although a higher proportion of sick individuals harbor this organism it can also be isolated from the genitourinary tract of healthy persons [5]. More recently there have been several reports which are suggestive of an etiologic role for *M. hominis* in some cases of sterility, abortion and post-partum septicemia [23, 27, 29, 38, 54, 55]. A new mycoplasma species called *M. lipophilae* was recently isolated from a patient suffering from pneumonia [15]. The pathogenicity of this organism remains to be determined.

The association of mycoplasma with arthritic conditions of animals has led to extensive studies designed to ascribe a mycoplasmal etiology to human arthritic diseases. The results of these studies have been inconclusive. However a wide variety of mycoplasma species including apparently non-pathogenic species as well as the agents of rat and swine arthritis have been isolated from patients with rheumatoid arthritis, disseminated lupus erythematosus and cancer [2, 3, 4, 22, 24, 26, 35, 36, 43]. The absence of any consistent association of a particular species with these conditions suggests that for the most part, the isolates obtained are in fact secondary invaders of diseased tissue rather than etiologic agents.

A distinct group of mycoplasmas, termed T strains, inhabit the mucus membranes of man and other animals. Although these organisms are similar morphologically to the Mycoplasmatales, they are characterized by the small size of the colonies on artificial media, by their metabolism of urea, preference for a lower pH and their rapid rate of growth and loss of viability in culture. It has been said that they contribute to non-gonococcal urethritis in man and may induce sterility [13, 18, 19, 20, 25].

With a few exceptions, comparatively little is known about the mechanisms of pathogenesis of mycoplasmal diseases. The neurologic disturbances which occur in mice infected with *M. neurolyticum* are known to be caused by a potent neurotoxin [53]. The brain lesions observed in turkeys infected with *M. gallisepticum* are also believed to be due to the action of a toxin [1]. The pathogenesis of *M. pneumoniae* for man is thought to be related to the production of large amounts of peroxide by this organism, and its ability to strongly adsorb to the epithelium of the respiratory tract [9, 46, 50].

## MYCOPLASMAS IN NON-HUMAN PRIMATES

Very few studies have been carried out on mycoplasmas in non-human primates. The first report concerning the isolation of simian mycoplasmas was that of TAYLOR-ROBINSON *et al.* [52]. These investigators demonstrated that an isolate obtained from the oropharynx of a *Cercopithecus* monkey was closely related serologically to the human commensal species *M. salivarium*. Subsequent genetic studies involving the hybridization of the DNA's from the simian and human strains confirmed a close, although not identical relationship between these organisms [49]. In another series of isolations a vaginal strain was found to be closely related to its human counterpart, *M. hominis*.

A preliminary report on a wide range of primate species was that of DAVIDSON and THOMAS [14]. Chimpanzees, baboons, black apes, siamangs, gibbons, rhesus, green and squirrel monkeys all harbored several species of mycoplasma in the throat. *M. salivarium* and *M. orale* type 2 were identified. Only one vaginal species, *M. hominis*, was encountered. The baboons were found to harbor several species of mycoplasma which were unrelated to the human species. In addition, DAVIDSON [personal communication] has repeatedly isolated *M. arthritidis* (*M. hominis* type 2) from a rhesus monkey. Although the natural habitat of this mycoplasma species is the rat, isolations have been reported from the urogenital tract of man [16]. In another report the isolation of T strain mycoplasmas from monkeys was mentioned [51].

Preliminary studies by the present authors of 8 Yerkes female chimpanzees have shown mycoplasmas to be present in one or more of swabs taken from the nose, throat, vagina, and rectum. These were compared with mycoplasmas obtained from human sources (table I). The techniques and analyses of the isolates were conducted according to standard practices [8, 10, 12, 31, 33, 39, 48, 52].

On the basis of growth requirements, colonial morphology and physiologic properties, four distinct types of mycoplasma could be recognized in the chimpanzee material obtained from the Yerkes Center (table II).

Type A strains were isolated from the saliva of 6 out of 8 animals. They were characterized by their preference for anaerobiosis, metabolism of arginine, lipolysis on egg yolk containing media and other lipid substrates, failure to reduce methylene blue or to ferment carbohydrates. The colonies were smooth with well-defined central areas of growth into the agar (fig. 2A). The isolates closely resembled *M. salivarium* of human origin. In addition these strains also produced the specific reaction of *M. salivarium* in which guinea-pig erythrocytes are protected against autolysis [12].

Table I. Source of chimpanzee and human mycoplasma strains from other laboratories

Species and strains	Source	Obtained from <sup>1</sup>
<i>M. salivarium</i> 156	Human oropharynx	M. F. BARILE
336-1 (related to <i>M. salivarium</i> )	Chimpanzee oropharynx	M. DAVIDSON
<i>M. hominis</i> 471	Human genital tract	P. E. PEASE
<i>M. hominis</i> TA	Lung of stillborn infant	P. E. PEASE
<i>M. hominis</i> 14027	Human genital tract	ATCC
467 (related to <i>M. hominis</i> )	Chimpanzee vagina	M. DAVIDSON
<i>M. pneumoniae</i> FH P176	Human atypical pneumonia	D. L. MADDEN
<i>M. orale</i> type 1 ST5	Human oropharynx	D. L. MADDEN
<i>M. orale</i> type 2 ST6	Human oropharynx	D. L. MADDEN
<i>M. orale</i> type 3 DC333	Human oropharynx	R. A. DEL GIUDICE
<i>M. lipophilis</i> MaBy	Human pneumonia patient	R. A. DEL GIUDICE
<i>M. fermentans</i> G	Human genital tract	D. G. ff EDWARD

1 M. F. BARILE, Division of Biologic Standards, Bethesda, Md.; M. DAVIDSON, New York University Medical Center, New York, N.Y.; P. E. PEASE, University of Birmingham, England; ATCC, American Type Culture Collection, Rockville, Md.; D. L. MADDEN, National Institute of Allergy and Infectious Disease, Bethesda, Md.; R. A. DEL GIUDICE, Baltimore Biological Laboratories, Cockeysville, Md.; D. G. ff EDWARD, Wellcome Research Laboratories, Kent, England.

Type B strains were isolated in large numbers from the vaginas of 7 out of 8 animals and from the rectal swabs of two animals. Two animals harbored this species in small numbers in the saliva. Type B strains grew aerobically and anaerobically and were characterized by the production of rough colonies with central regions of agar growth (fig. 2B, C). Arginine was metabolized but carbohydrates were not fermented. Triphenyltetrazolium chloride was weakly reduced under anaerobic conditions only and no lipolysis was apparent on egg yolk media. Methylene blue was not reduced. The isolates closely corresponded with *M. hominis* (type 1) of human origin.

The type C strains were isolated under anaerobiosis from the vaginas of two animals. Colonies were slow to develop and were initially somewhat irregular in appearance (fig. 2D). In culture the colonies would either remain



Table II. Source of chimpanzee mycoplasmas isolated in present studies

Animal name	Number of species harbored	Isolated from	Strain	Type designation
Barfy	2	vagina	BV1	B
			BV2	C
Victoria	2	saliva	VS	A
		vagina	VV	B
Cheri	3	saliva	ChS	A
		vagina	CV1	B
			CV2	C
		rectum	CR	B
Helene	2	saliva	HS	A
		vagina	HV	B
Ada	2	saliva	AS1	B
			AS2	B
			AS3	A
Maria	2	saliva	MS	A
		vagina	MV	B
Wendy	2	saliva	WS1	B
			WS2	D
		vagina	WV	B
Vera	2	saliva	VeS	A
		vagina	VeV	B
		rectum	VeR	B

small or grow larger and become smooth in appearance (fig. 2E, F). When the latter occurred they were mucoid in consistency. Glucose was fermented weakly but arginine was not metabolized. No evidence of lipolysis was present on egg-yolk-containing medium. Methylene blue was reduced in 24 h under anaerobic conditions using the test described previously [10]. Triphenyltetrazolium chloride was not reduced aerobically but was strongly reduced anaerobically with the production of numerous dark red crystals. Peroxide production was positive as detected by the benzidine reaction. Moderate  $\beta$ -hemolysis occurred on guinea-pig and human erythrocytes; weak  $\alpha$ -hemolysis occurred with rabbit, sheep, duck and chicken erythrocytes. Group C strains were quite unlike any of the human species and, on the basis of pre-

viously published reports and our own observations, they could readily be differentiated from the other non-human mycoplasmas.

Type D was represented by one isolate obtained from saliva, under anaerobiosis. Colonies were smooth but somewhat smaller than the group A strains. Arginine was metabolized but no signs of lipolytic activity were evident. Carbohydrates were not fermented. Triphenyltetrazolium chloride was reduced only anaerobically. Methylene blue was not reduced. Hemolysis of animal erythrocytes was very weak or absent. Peroxide production was not detected, and guinea-pig erythrocytes were not protected against autolysis. The growth and physiologic properties of this organism resemble *M. orale* types 1 and 2.

The physiologic properties of the chimpanzee isolates and representatives of the human species are recorded in table III.

Table III. Physiologic characteristics of chimpanzee and human mycoplasma strains

Strains	aerobic growth	NH <sub>3</sub> from arginine	glucose fermentation	TTC reductn. aerobic	TTC reductn. anaerobic	methylene blue reductn.	hemadsorption	peroxide prodn.	lipolysis egg yolk	protective factor
Chimp. type A	-	+	-	-	+c	-	-	-	+	+
336-1	-	+	-	-	+c	-	-	-	+	+
<i>M. salivarium</i> 156	-	+	-	-	+c	-	-	-	+	+
Chimp. type B	+	+	-	-	w	-	-	-	-	-
467	+	+	-	-	w	-	-	-	-	-
<i>M. hominis</i> 14027	+	+	-	-	w	-	-	-	-	-
Chimp. type C	-	-	w	-	++c	+	-	+	-	-
Chimp. type D	-	+	-	-	+	-	-	-	-	-
<b>Other human species:</b>										
<i>M. orale</i> type 1	-	+	-	-	+	-	-	-	-	-
<i>M. orale</i> type 2	-	+	-	-	+	-	-	-	-	-
<i>M. fermentans</i>	-	+	+	-	+	-	-	w	+	-
<i>M. pneumoniae</i>	+	-	+	+	+	+	+	++	-	-

- negative reaction                      + or ++ positive or strong positive reaction  
w weak positive reaction                c crystal deposition

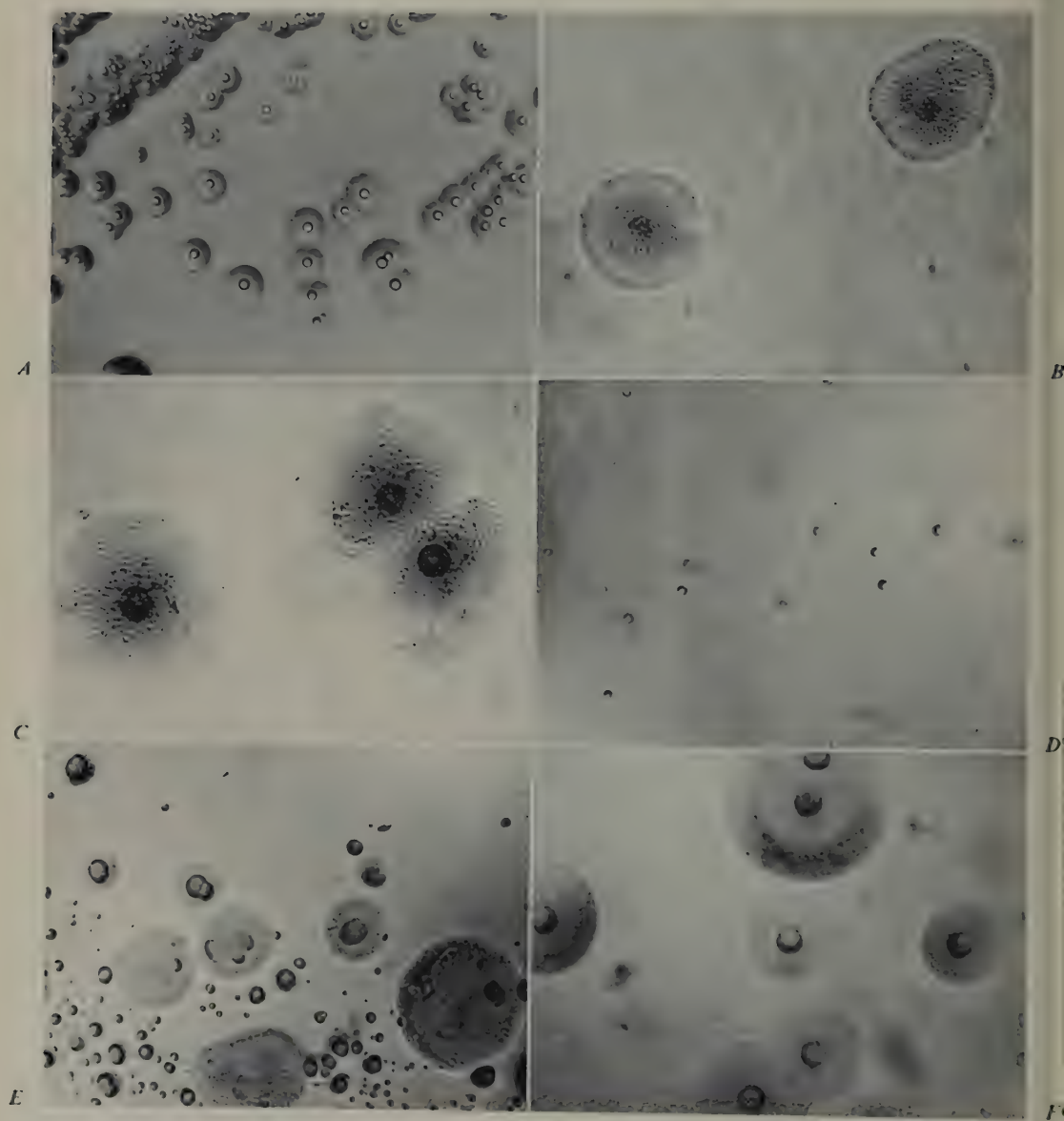


Fig. 2. *A* Smooth colonies typical of the type A strains (*M. salivarium*) after 5 days of anaerobic incubation. Note the well-defined central areas of growth into the agar (magn.  $\times 20$ ). *B* and *C* Rough colonies of the type B strains (*M. hominis*) after 3 and 7 days respectively of aerobic incubation (magn.  $\times 30$ ). *D* Small irregular colonies of the type C strains before mucoid phase, 7 days of anaerobic incubation (magn.  $\times 30$ ). *E* and *F* Type C colonies showing various stages of mucoid growth, 7 to 10 days of anaerobic incubation (magn.  $\times 30$ ).

In order to further investigate the identity of the chimpanzee isolates, antisera were prepared in rabbits against representative strains from each of the four types isolated. Antigens and antisera of these strains were reacted against the human species. For comparative purposes chimpanzee strains were tested serologically against a wide range of mycoplasma species of animal origin.

The most specific serologic test for the identification of mycoplasmas is that of inhibition of growth in the presence of specific antiserum. The procedure used was that of CLYDE [8] in which serum impregnated discs are placed on the surface of an agar plate just after inoculation with the mycoplasma being tested. After incubation, a zone of inhibition of the mycoplasma colonies around the disc is produced in the homologous system. The degrees of inhibition produced by the various antisera are recorded in table IV.

All of the type A strains were inhibited to varying degrees by antiserum against strain Ch.S. *M. salivarium*, strain 156, and DAVIDSON's strain 336-1, thus confirming the close relationship of these organisms with *M. salivarium* of human origin. In addition, the type A strains were inhibited by antiserum against the type D strain WS2 and vice versa. As lipolytic activity was not originally detected for the type D strain all biochemical tests were repeated for this organism. The strain was cloned an additional 4 times in order to exclude contamination. The results were identical to those originally obtained. Furthermore, the cloned culture reacted identically in the serological tests.

On the basis of growth inhibition the type B strains were found to be somewhat heterogeneous. Two groups could be defined. Group 1 strains were inhibited by antiserum prepared against the human strains *M. hominis*, 14027 and PG 21<sup>1</sup>. Strain 467 of DAVIDSON was included in this group as well as three of our own chimpanzee isolates. Group 2 strains were not significantly inhibited by *M. hominis* 14027 antiserum, but were strongly inhibited by their homologous sera. The close relationship of groups 1 and 2 was evident by the observation that some strains were inhibited by both 14027 serum (group 1) and group 2 serum (table V). Prolonged incubation of the plates resulted in the formation of a narrow zone of precipitation surrounding the discs at a distance of 5-10 mm. This band was caused by the reaction of a soluble antigen produced by the mycoplasmal growth and

1 Antiserum against strain PG 21 was kindly supplied by the Division of Infectious Diseases, University of Utah College of Medicine.



Table IV. Relationship of type A, C and D chimpanzee strains to human species by the growth inhibition test of CLYDE

Strain	Specific rabbit antisera against								
	Chimpanzee strains						<i>M. orale</i>		
	<i>M. sal.</i> 156	Ch. S. type A	WS2 type D	336-1 type A	CV2 type C	BV2 type C	type 1	type 2	type 3
<i>M. sal.</i> 156	+	s	s	+	-	-	-	-	-
Ch. S (A)	+	+	+	+	-	-	-	-	-
WS2 (D)	+	+	+	s	-	-	-	-	-
336-1 (A)	+	+	+	+	-	-	-	-	-
HS (A)	++	+	+	++	-	-	-	-	-
MS (A)	+	s	s	++	-	-	-	-	-
AS3 (A)	+	++	+	+	-	-	-	-	-
VS (A)	+	++	s	++	-	-	-	-	-
CV2 (C)	-	-	-	-	++	++	-	-	-
BV2 (C)	-	-	-	-	++	++	-	-	-
<i>M. orale</i> type 1	-	-	-	-	-	-	+++	-	-
<i>M. orale</i> type 2	-	-	-	-	-	-	-	++	-
<i>M. orale</i> type 3	-	-	-	-	-	-	-	-	++
+++ Zone of inhibition 6 mm or more									
++ Zone of inhibition 3-5 mm									
+ Zone of inhibition 0-2 mm									
- None									

homologous antibody diffusing from the disc. This reaction was common to all of the type B strains irrespective of the extent of growth inhibition. Similar though weaker reactions were observed between the type A strains. There was no evidence of cross reactivity between type A and type B strains.

The type C strains were found to be identical on the basis of growth inhibition. They did not react with any of the human species or the following animal species of mycoplasma: *M. spumans*, *M. canis*, *M. maculosum*, *M. felis*,

Table V. Relationship of *M. hominis* strains of human origin to the chimpanzee type B strains by the growth inhibition test of CLYDE

Strains	Specific rabbit antisera against				
	<i>M. hominis</i> strains (human)		Chimpanzee strains		
	14027	PG 21	467	VV	ASI
Human					
14027	+++	++	++	+	+
TA	+++	+++	+++	—	—
Chimpanzee					
467	+++	+++	+++	++	+
WV	+++	++	+++	++	+
WS1	+++	.	.	—	—
CV1	+++	.	.	—	—
VV	—	—	—	+++	++
AS1	—	—	—	+++	+
AS2	—	—	—	++	+
BV2	—	—	—	+++	+
HV	—	—	—	+++	++
MV	—	—	—	+++	++
VeV	—	.	.	++	++
VeR	—	.	.	++	++
+++ Zone of inhibition 6 mm or more					
++ Zone of inhibition 3–5 mm					
+ Zone of inhibition 0–2 mm					
— None					

*M. gateae*, *M. leonis*, *M. arthritis*, *M. pulmonis*, *M. neurolyticum*, *M. gal-lisepticum*, *M. gallinarum*, *M. iners*, *M. hyorhinis*, *M. granularum*, *M. bovi-genitalium*.

A more sensitive procedure for growth inhibition is the metabolic inhibition test of PURCELL *et al.* [39]. In this test growth inhibition is measured by failure of the organisms to metabolize a given substrate in the presence of various dilutions of specific antiserum. In the present study which was confined to the *M. hominis* strains, the test was conducted using arginine as the substrate and phenol red as an indicator of arginine dihydrolase activity. The titer recorded corresponded to the reciprocal of the highest dilution of

antiserum which inhibited arginine metabolism. The test was read when the control tube containing no antiserum changed approximately 0.5 of a pH unit. The results obtained with the *M. hominis* strains are recorded in table VI. Excellent correlation was obtained between the growth inhibition test and metabolic inhibition tests. The group 1 antisera inhibited the group 2 strains

Table VI. Relationship of chimpanzee and human *M. hominis* strains by the metabolic inhibition test (MI)

Strains	Reciprocal of MI antibody titers using rabbit antisera against			
	<i>M. hominis</i> 14027 (gp. 1)	Chimp. 467 (gp. 1)	Chimp. VV (gp. 2)	Chimp. AS2 (gp. 2)
Human strains				
14027	2560	640	160	80
471	640	160	20	<20
TA	> 10240	1280	160	40
Chimp strains				
WV	5120	> 10240	640	640
WS2	1280	640	80	80
467	5120	5120	160	40
VV	<20	20	5120	2560
AS2	40	20	5120	2560
VeV	160	40	10240	5120

Table VII. Distribution of chimpanzee strains of mycoplasma

	Number of isolations from				
	oropharynx	vagina	urine	nose	rectum
<i>M. salivarium</i> (type A)	6/8	0/8	0/8	0/8	0/8
<i>M. hominis</i> (type B) gp. 1	1/8	2/8	0/8	0/8	1/8
gp. 2	1/8	5/8	0/8	0/8	1/8
Type C	0/8	2/8	0/8	0/8	0/8
Type D	1/8	0/8	0/8	0/8	0/8

at low titers only and vice versa, thus confirming the non-identity of the two groups.

The distribution of the various chimpanzee mycoplasmas is recorded in table VII.

For the purposes of a general survey, the mycoplasmal flora of a variety of primates is currently being investigated. The orang-utan is being extensively studied. *M. hominis* has not been isolated from these animals. As a result of physiologic and serologic investigations we have identified the presence of five distinct species of mycoplasma. Strains related to *M. salivarium*, *M. orale*, type 1 and *M. orale* type 2 have been identified. The remaining two species appear to be distinct from the other human species and distinct from the type C chimpanzee mycoplasmas. Preliminary work on the gorilla, indicates that it also harbors several species of mycoplasma. As with the orang-utan, *M. hominis* has not been isolated from these animals.

Our observations, together with other available data, establish that non-human primates harbor several species of mycoplasma. The isolation of strains related to *M. hominis* and *M. salivarium* of human origin confirms the findings of other investigators. The exact relationship of the type D strain to *M. salivarium* remains to be determined, but the serological data suggest that it is very closely related to the latter species. In addition we have characterized a new species of chimpanzee mycoplasma which could not be identified with any of the human or animal species to which it was compared. Current work [unpublished observations] indicates that the chimpanzee harbors other species of mycoplasma in addition to those described in this chapter.

The present data suggest that there are at least two main subgroups of *M. hominis*, both of which may be harbored by the chimpanzee. One of these appears identical to the human strains of *M. hominis* which were tested. The other group may represent a variant of *M. hominis*, specific to the chimpanzee. However it should be pointed out that in a study by PURCELL *et al.* [40] comparisons between several human species of *M. hominis* indicated some serologic heterogeneity. Thus the chimpanzee variant described by the present authors may, in fact, prove to be identical with other human strains. The differences in cross-reactivity observed between our two groups of *M. hominis*, were greater than those observed by PURCELL *et al.* between their human strains. This would indicate that the chimpanzee group 2 strains may be distinct from the others. Both groups of *M. hominis* possessed the soluble antigenic component visualized on the growth inhibition plates as a zone of precipitation. This antigen appeared to be specific for all of the *M. hominis* strains.



Genetic studies by SOMERSON *et al.* [49] indicated that differences were detected between a human and simian strain of *M. hominis*. While it is clear that two distinct strains were involved in these studies, it cannot be concluded that these strains are specific for the host from which they were isolated. Genetic studies on a large number of strains would be required before this assumption could be made.

At this time it is not possible to state whether the human mycoplasma species harbored by chimpanzees constitute the natural flora of these animals or whether they have been acquired through human contact during captivity. Examination of these animals immediately following capture would be necessary to elucidate this question. Further evidence for the natural occurrence of human species in primates would be obtained if it could be conclusively shown that one particular genetic type was harbored only by the chimpanzee. This study would involve an extensive survey on many strains. It may be significant that of all of the great apes cultured in our laboratory, only the chimpanzee has so far been found to harbor *M. hominis*.

The studies reported in this chapter represent a part of a general survey on the mycoplasmal flora of non-human primates. The survey was undertaken for several reasons. Firstly, nothing is known concerning the role of mycoplasma in diseases of these animals. The necessary preliminary work toward this goal is the characterization of the normal mycoplasmal flora. Once this is known there would be less risk in confusing the normal flora with potentially pathogenic isolates from diseased tissue. The invasion of such tissue by normally non-pathogenic microorganisms is a common occurrence. A further aspect of these studies should involve the determination of the various species isolated and the periods of time during which they are harbored. Some mycoplasmas will undoubtedly be permanent commensal inhabitants, whilst others may prove to be transient, being rapidly eliminated by host defense mechanisms. The lack of information in this respect has led to controversy concerning the prevalence of *M. arthritidis* in man. Isolates of this organism obtained from the human genital tract were previously referred to as *M. hominis* type 2. Recently, more detailed studies have failed to differentiate these strains from *M. arthritidis*, a rat pathogen [11, 16, 32, 41, 49]. It has been reported that this organism was isolated from patients with rheumatoid arthritis [4]. In addition, specific complement-fixing antibodies were detected in the sera taken from these individuals. The presence of circulating antibody is often used as a measure of active or past infection, so the possibility exists that the *M. arthritidis* was a factor in the disease. As no information is available concerning the presence of circulating antibody

in normal individuals harboring *M. arthritidis* no definite conclusions can be made from these observations. Thus future investigations of non-human primates should include serologic studies. Animals should be surveyed for the presence of circulating antibodies produced as a result of the normal carriage of mycoplasmas. Furthermore, the type of antibody and its persistence in response to experimental infection should be known in order to perform a valid study of prevalence of past infections with mycoplasmas. This information will help in investigating the role of mycoplasmas in non-human primate diseases.

The mechanisms of pathogenicity of non-human primate diseases should be studied with a view to providing information relating to human disease. However, a more direct approach to human disease can be undertaken. As stated previously, considerable controversy exists concerning the role of mycoplasma in various diseases of man. The experimental use of non-human primates for this research would be of considerable value. If non-human primates are to be used in the studies, it is clear that many precautions must be taken. Ideally the species of primate to be chosen should be that which is the most closely related to man and yet does not naturally harbor mycoplasmas closely related to the human strains. Thus the mycoplasmal flora of the animal should be known prior to experimentation. It is important that the organisms to be implanted can be differentiated from those already present. If this latter condition cannot be met, the mycoplasma flora of the animal must at least be known. For reasons discussed previously, the presence of circulating antibody must be known prior to infection as well as after implantation of the test organisms.

Non-human primates have considerable potential value as experimental animals in the study of mycoplasmal disease of man. Because mycoplasma apparently show high specificity for producing disease only in closely related animal species, a non-human primate would be the logical experimental animal. *M. pneumoniae* is an established human pathogen and published reports indicate that *M. hominis* may also be pathogenic. Other species have been implicated in a variety of diseases but direct or conclusive demonstration of their pathogenesis has not been established. There are now eight species of mycoplasma which have been recovered from man, most of which have not been associated with disease. Because these other species have shown no consistent correlation with diseases of man, the non-human primate can be utilized to study their virulence and pathogenicity. This is particularly important for those species which may potentially produce serious disease and preclude human volunteer studies.

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Authors' addresses: Dr.B.C.COLE and Dr. J. R. WARD, Department of Internal Medicine, Division of Arthritis, University of Utah College of Medicine, Salt Lake City, UT 84112; Dr. C.E. GRAHAM, Yerkes Regional Primate Research Center, Emory University, Atlanta, GA 30322 (USA).

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